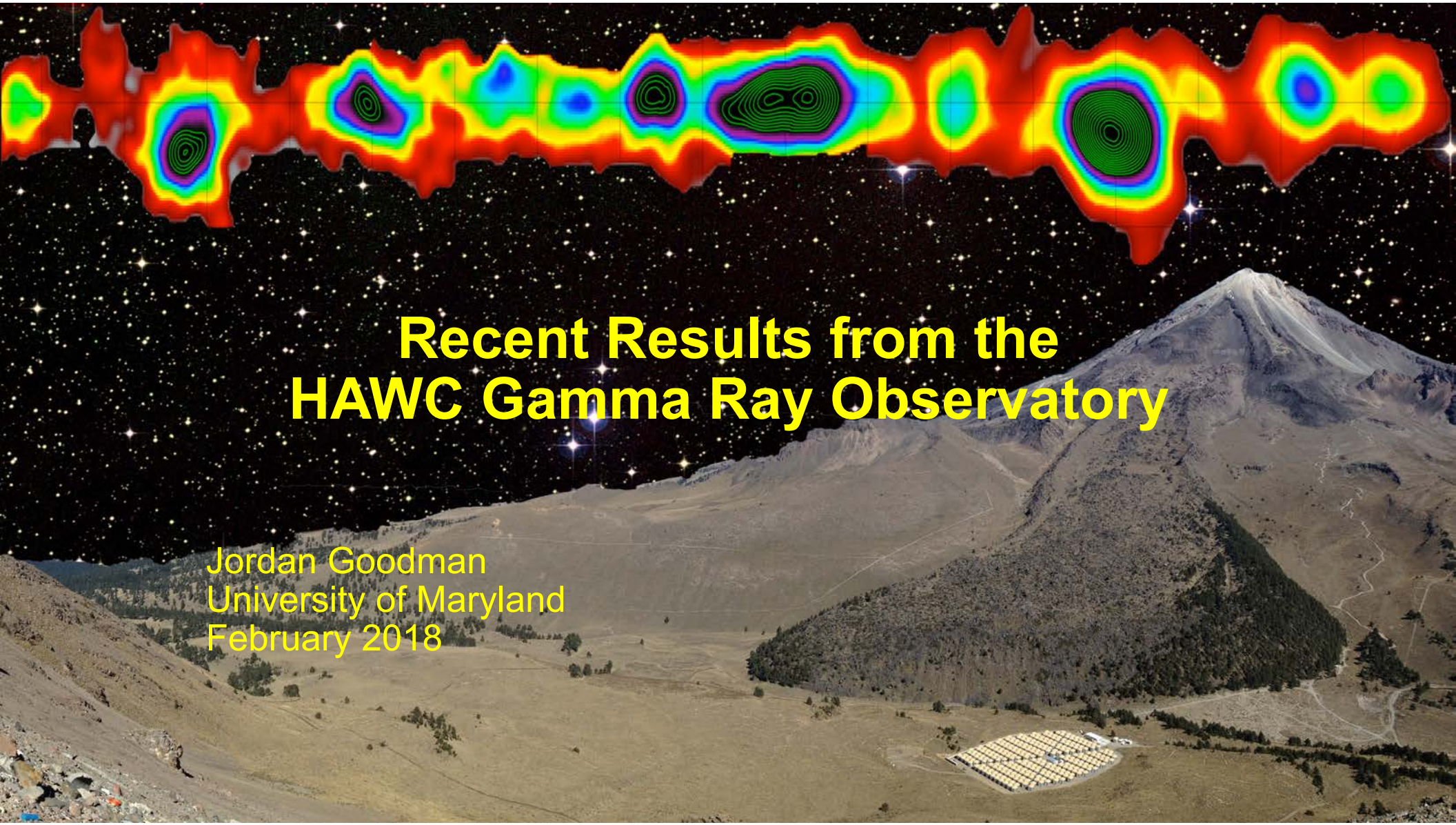
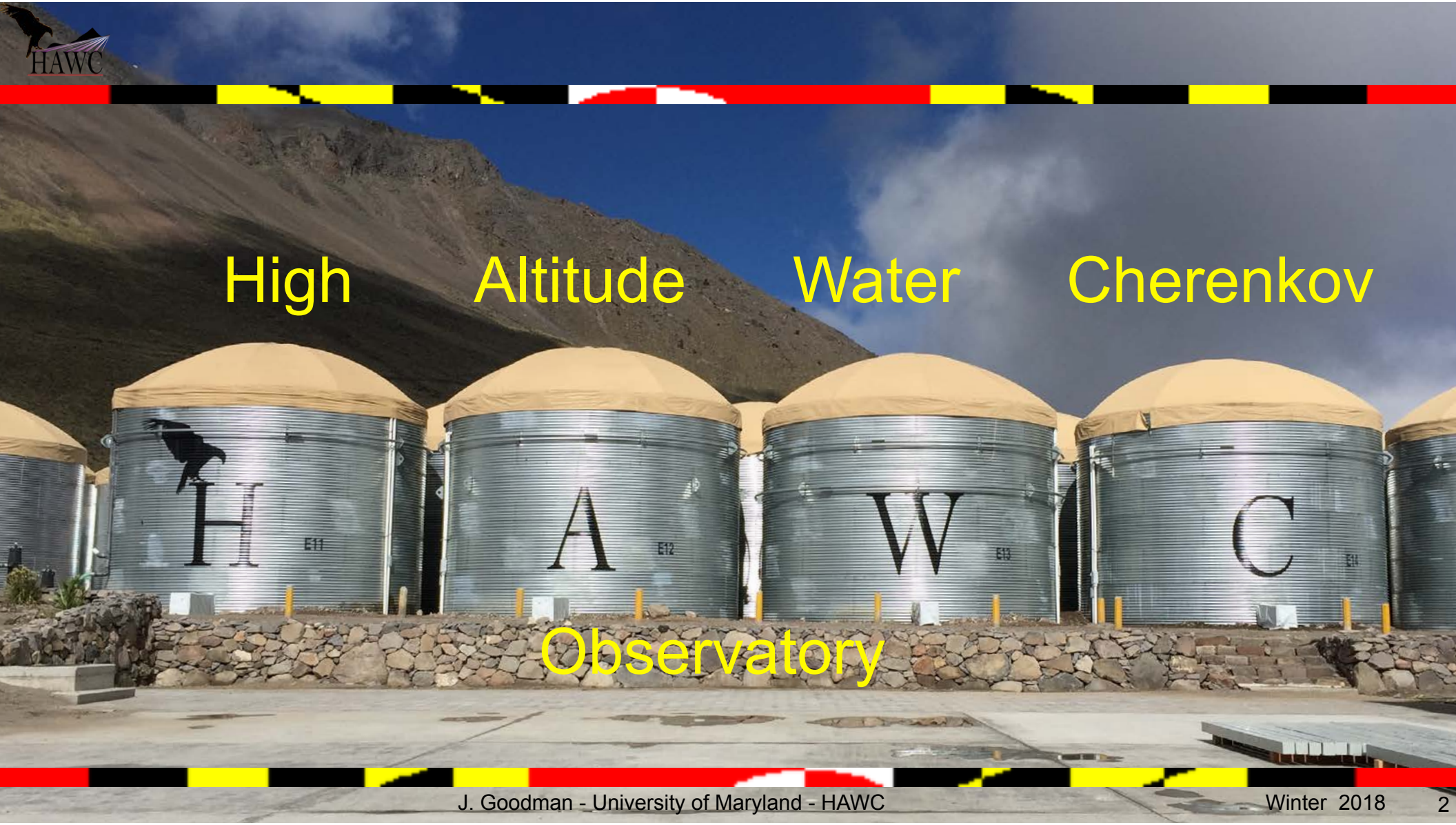


Recent Results from the HAWC Gamma Ray Observatory

Jordan Goodman
University of Maryland
February 2018


High Altitude Water Cherenkov
Observatory

The HAWC Collaboration

United States

University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology
Colorado State University
Michigan State University
University of Rochester
University of California Santa Cruz

Mexico

Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
- Instituto de Física
- Instituto de Astronomía
- Instituto de Geofísica
- Instituto de Ciencias Nucleares

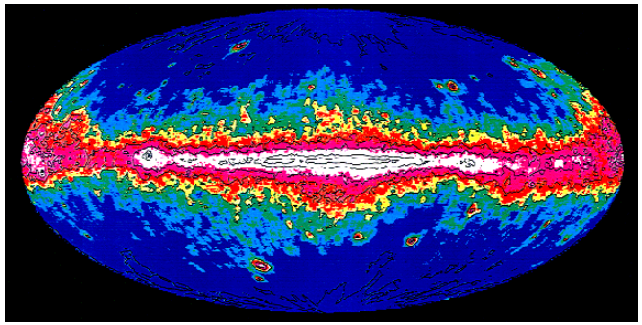
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación - IPN

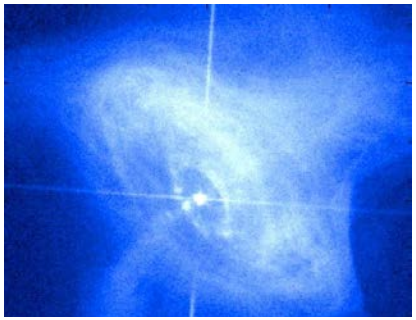
Europe

Max-Planck Institute for Nuclear Physics
IFJ-PAN, Krakow, Poland

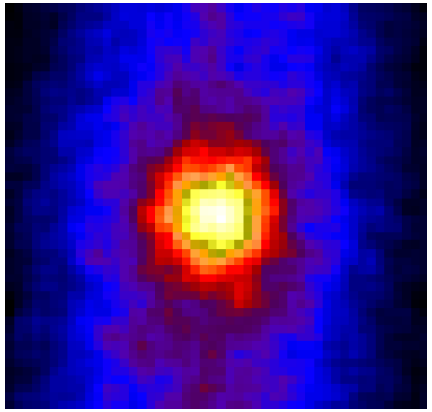
Multi-Messenger Astronomy

γ-rays

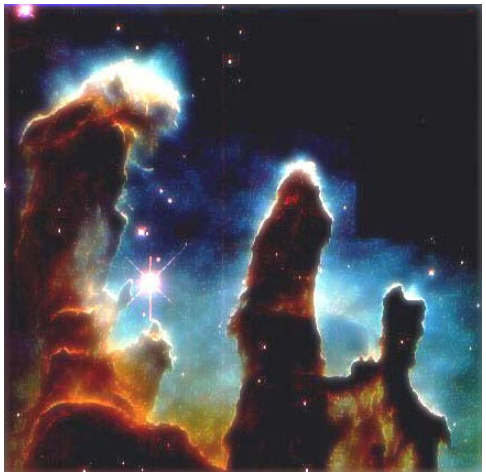




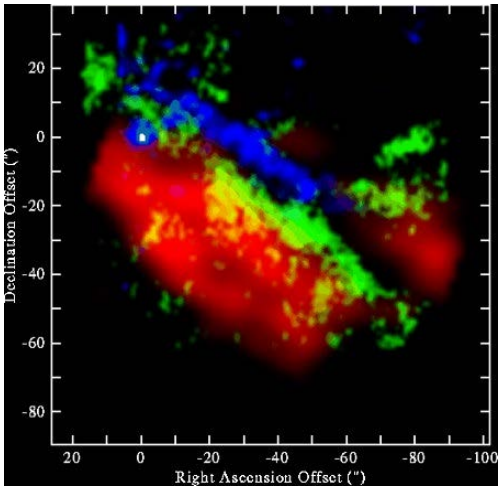
x-rays



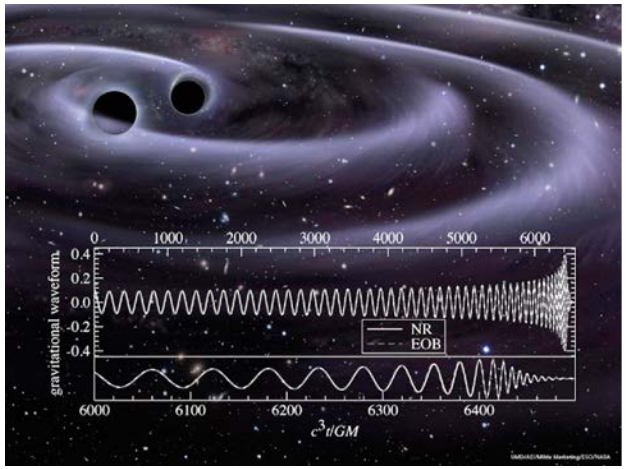
Neutrinos



visible



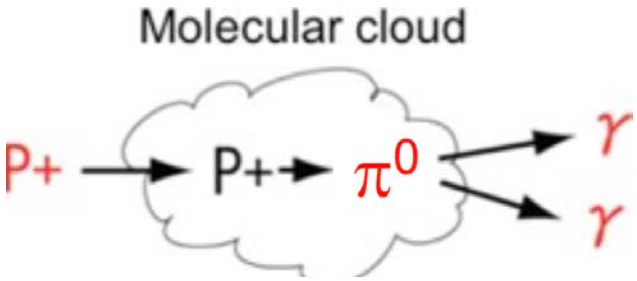
radio

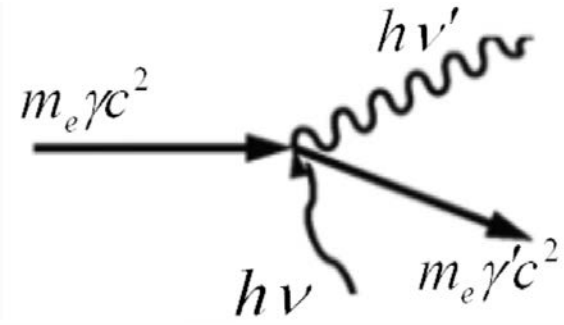


Gravitational Waves

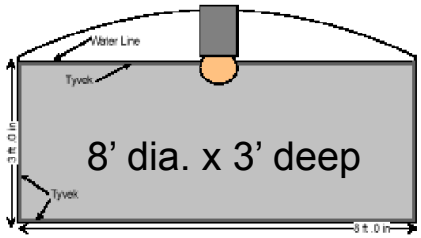
What Makes High Energy Gamma Rays

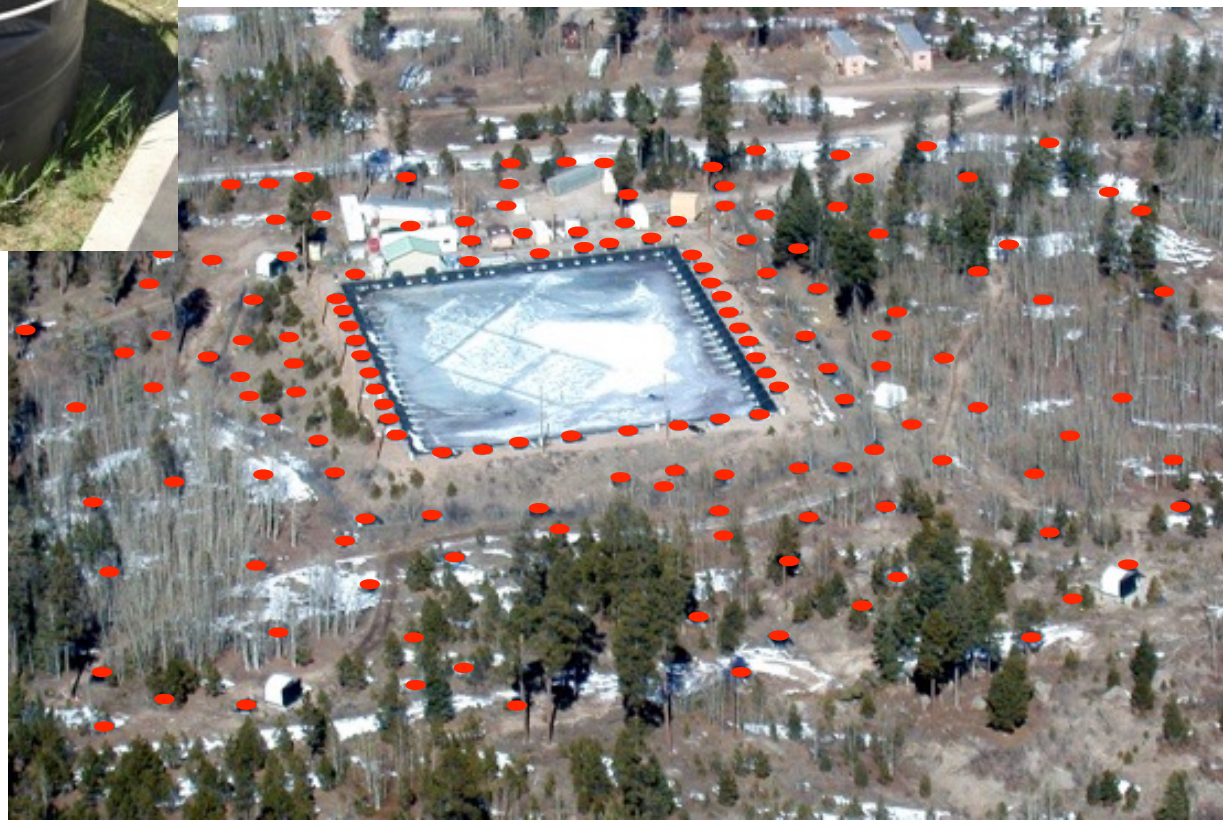
- Either hadronic or leptonic in origin
- Hadronic production comes from P-P collisions and then pion decay
- Leptonic production comes from inverse Compton Scattering
  - At energies above ~30 TeV the Compton drops (Klein-Nishina)
- So if spectra break they are likely leptonic if not they are more likely hadronic



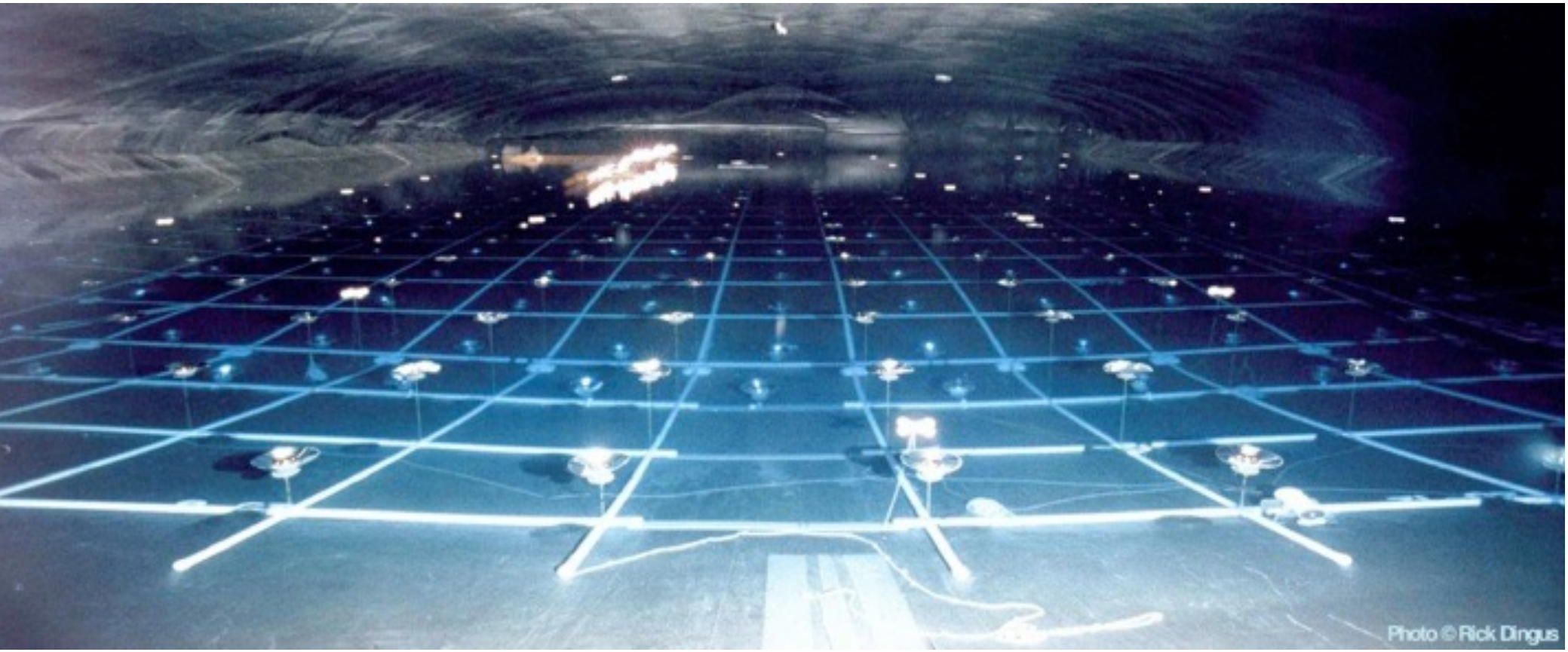


Milagro Pond and Array of 175 Outriggers

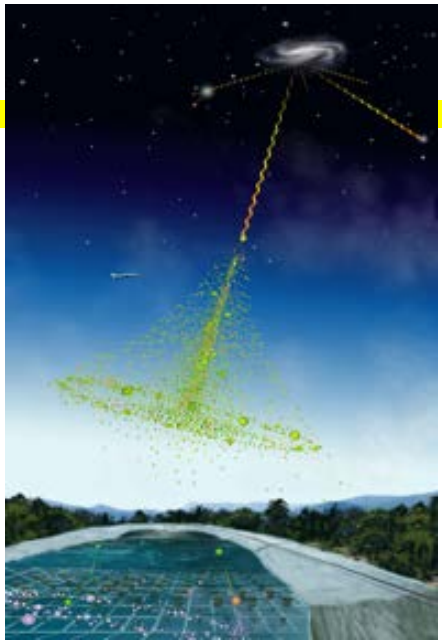




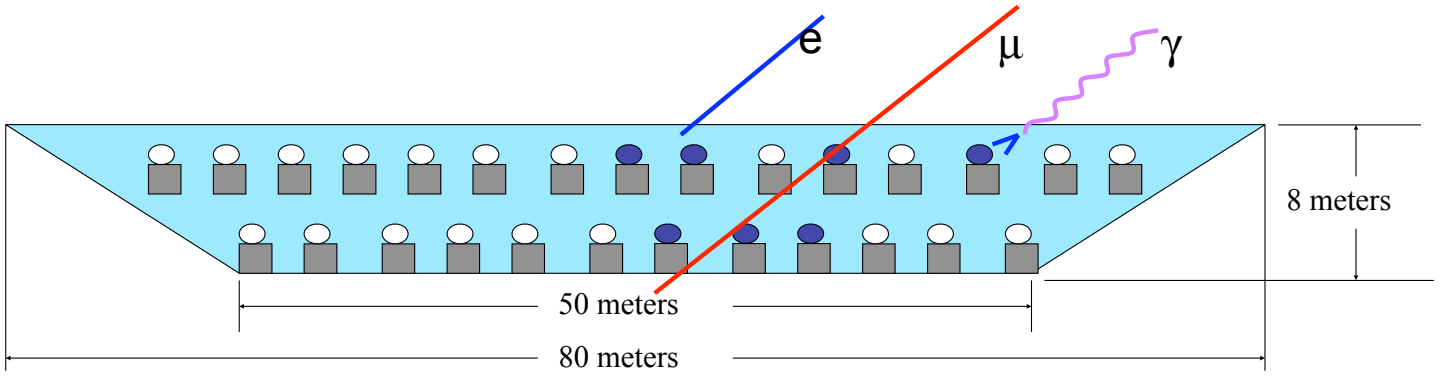
Inside the Milagro Detector



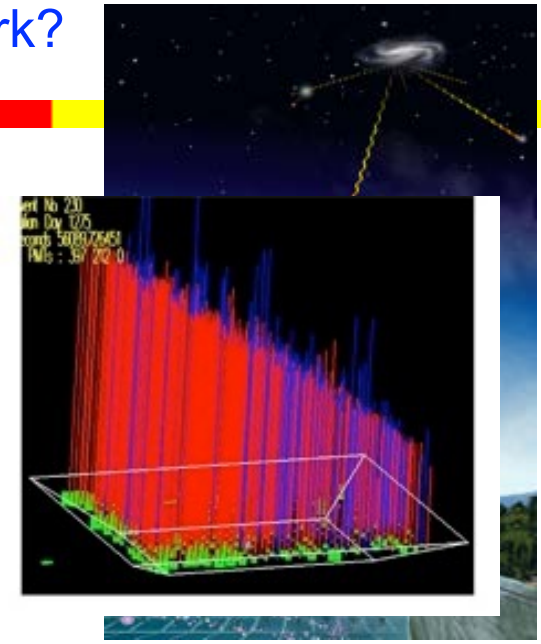
How Does Milagro Work?



- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water
- Reconstruct shower direction to ~0.5° from the time different PMTs are hit
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Field of view is ~2 sr and the average duty factor is >90%



How Does Milagro Work?



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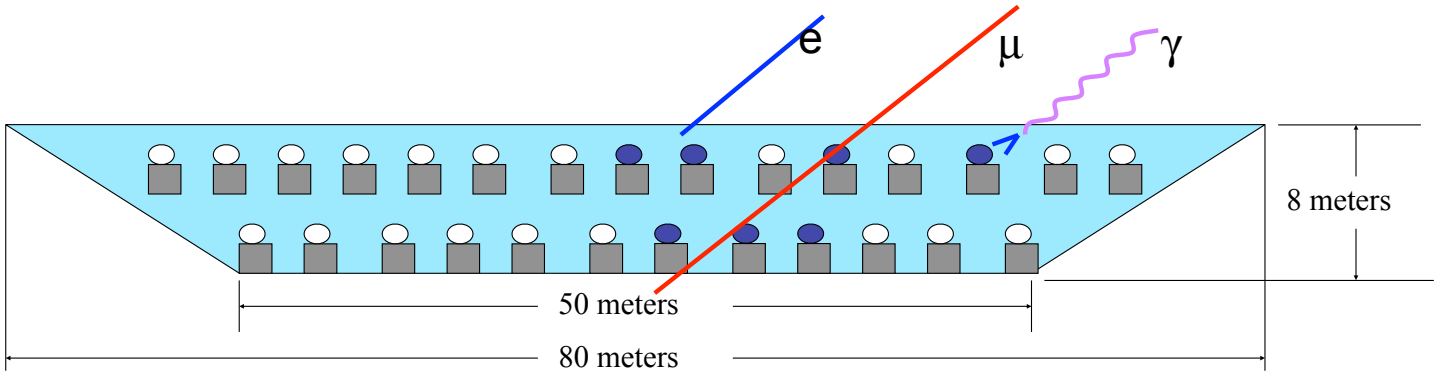

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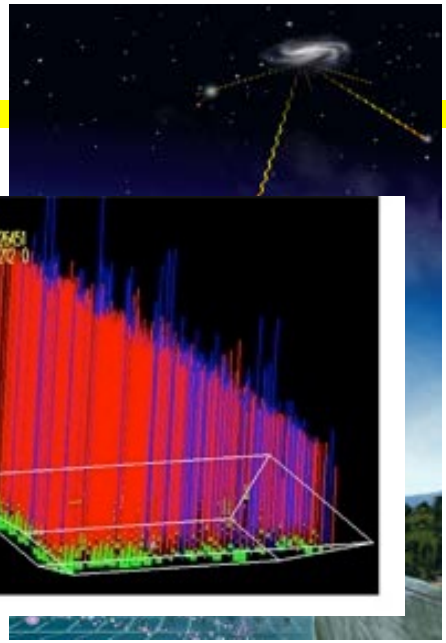

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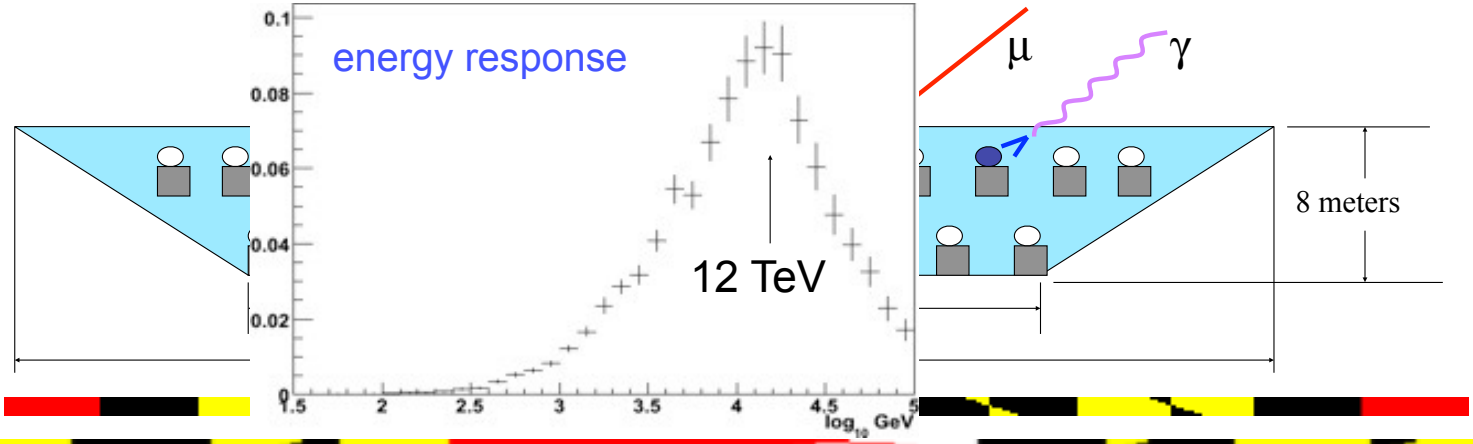
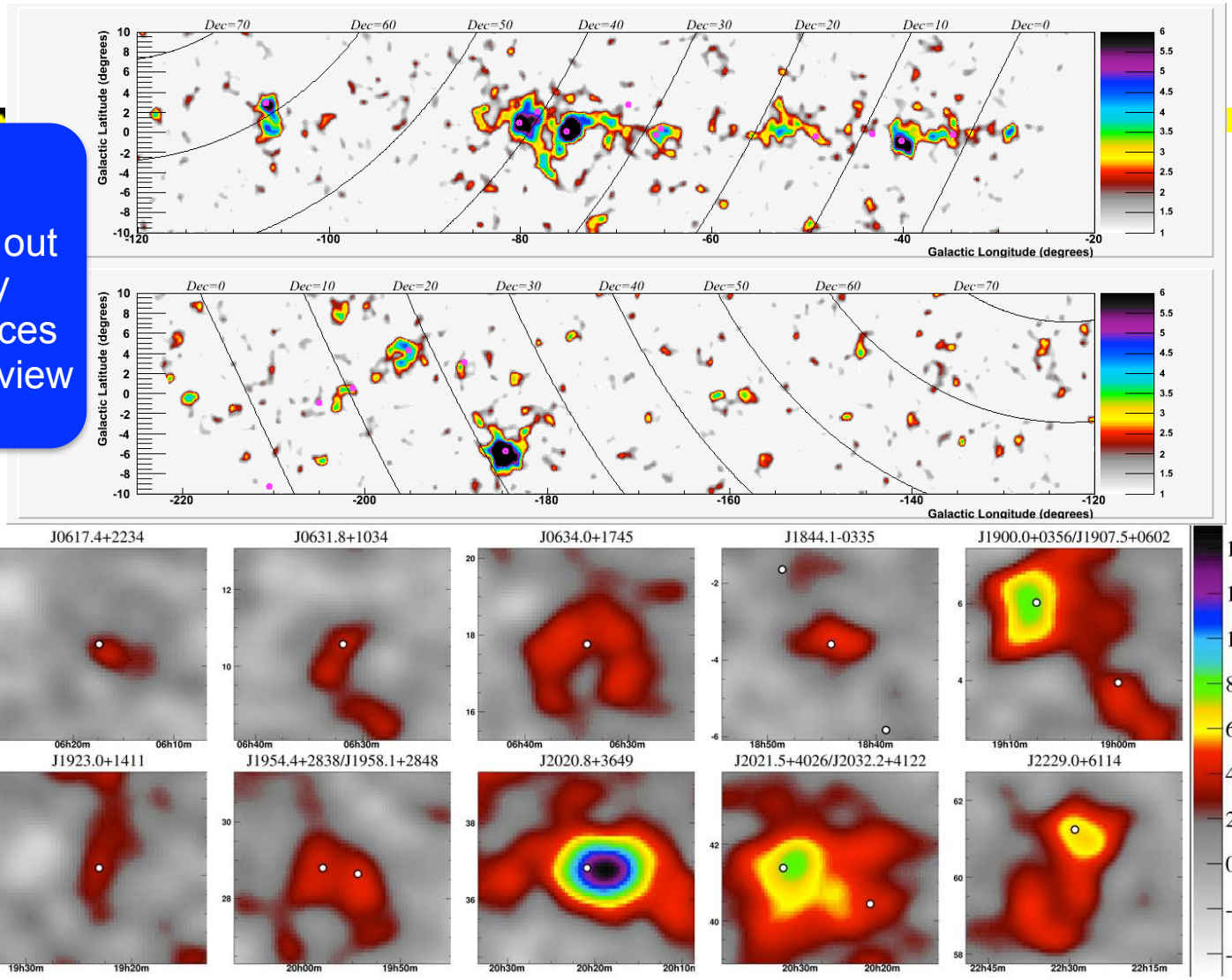


16 TeV associations out of 34 likely galactic sources in our field of view

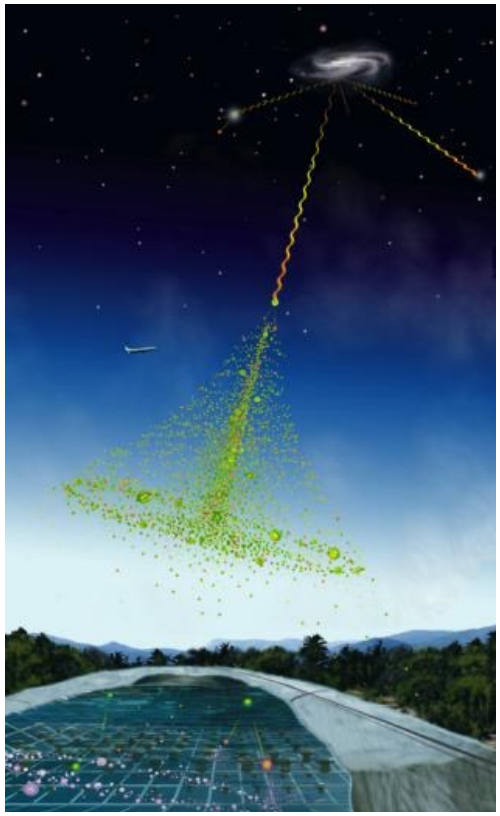


Abdo et al ApJL Apr 2009

HAWC Design builds on Milagro

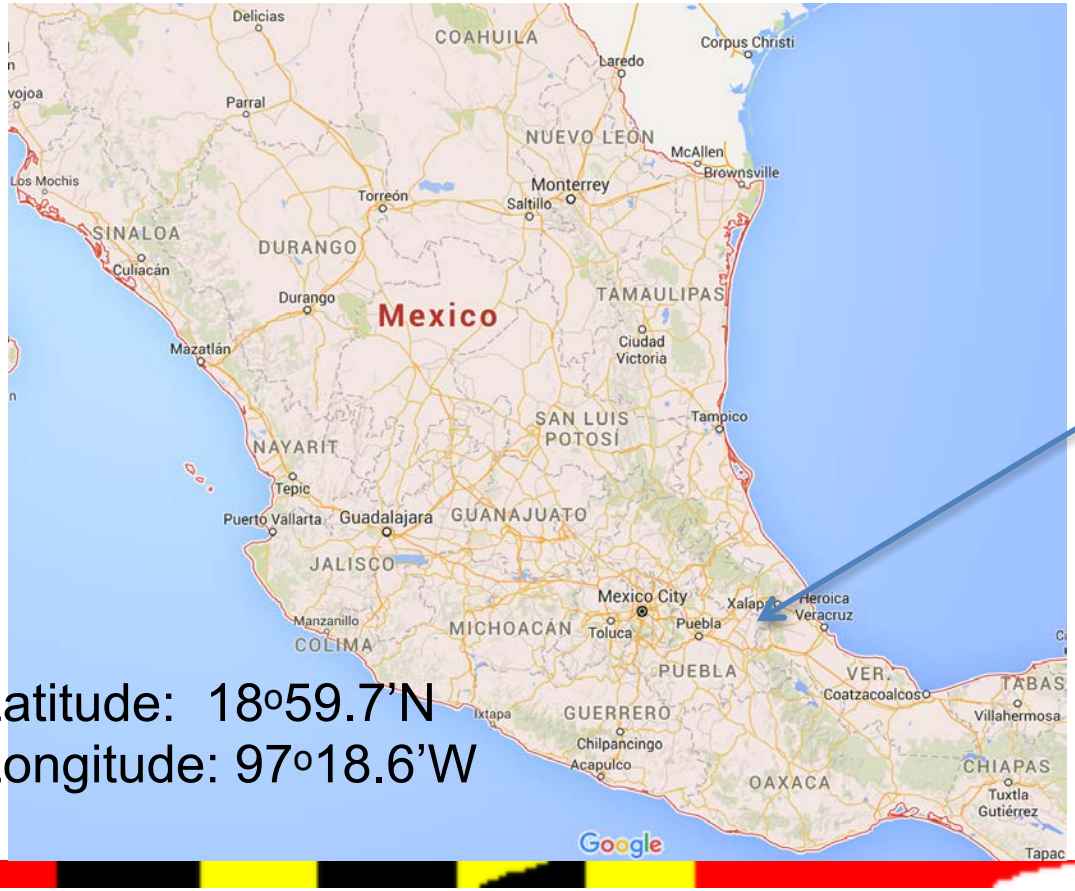
Milagro "1st Generation" Water Cherenkov detector
- 2650m (8600') elevation near Los Alamos, NM
- Covered pond of 4000 m^2
- Operated 2000-2008
- Crab at 5σ in 4-5 months

HAWC "2nd Generation" Water Cherenkov detector
- 4100m (13500') elevation near Puebla, Mexico
- 300 water tanks spread over 22,000 m^2
- Operation 2015-19(25)
- Crab at >5σ in a day



©Aurore Simonnet

The HAWC Site

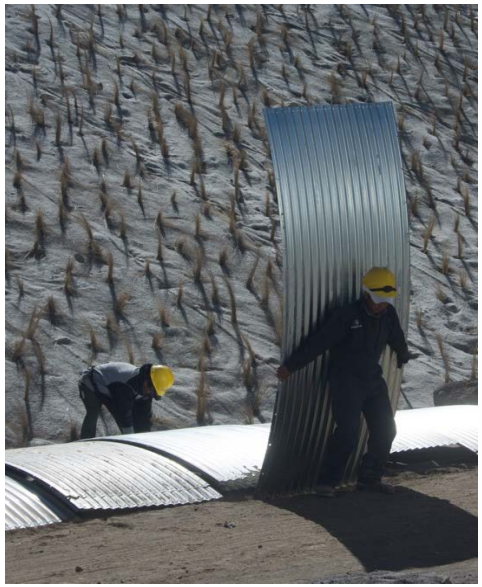


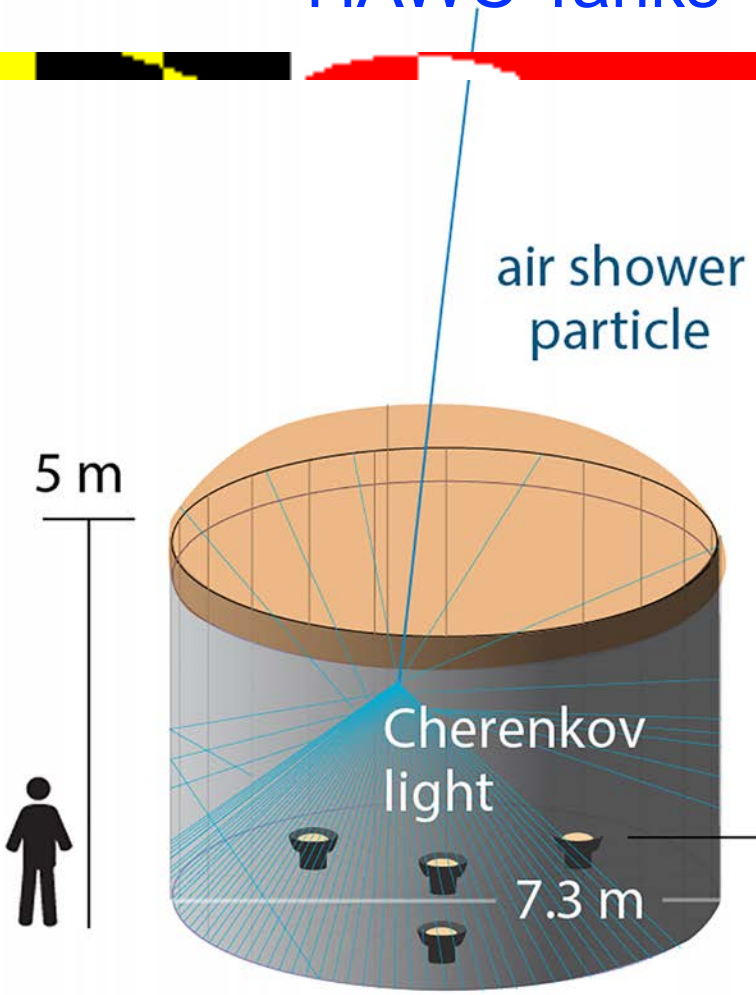
Latitude: 18°59.7'N
Longitude: 97°18.6'W

The HAWC Site

Latitude: 18
Longitude: 9

HAWC Tanks

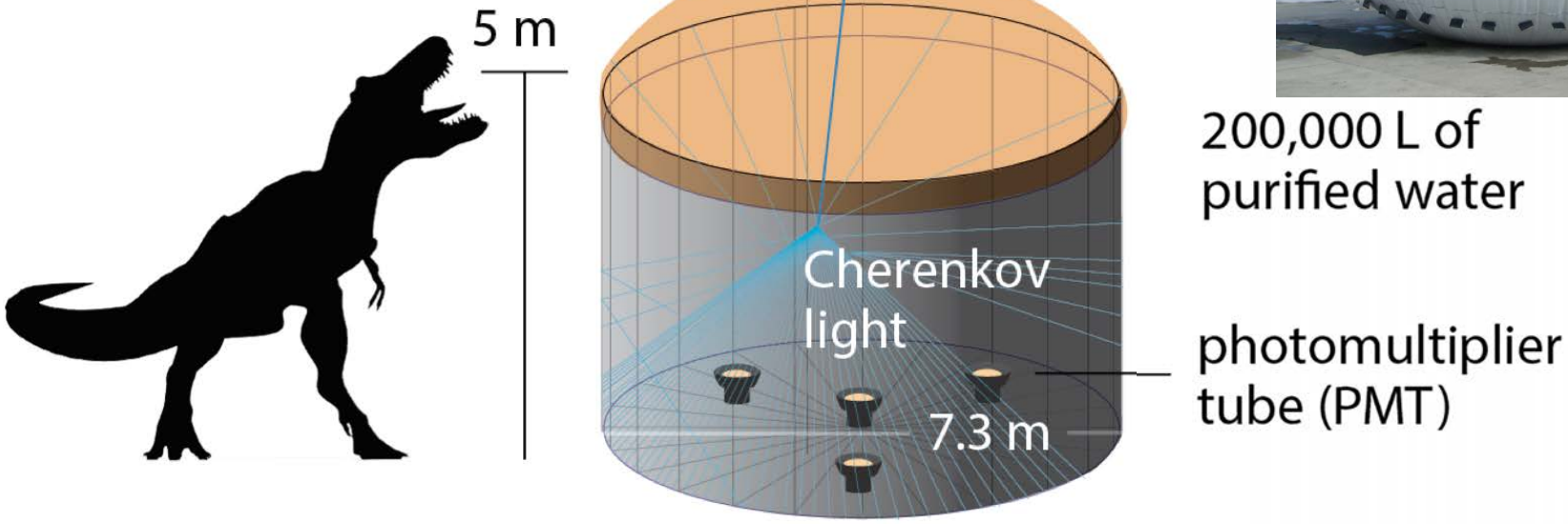




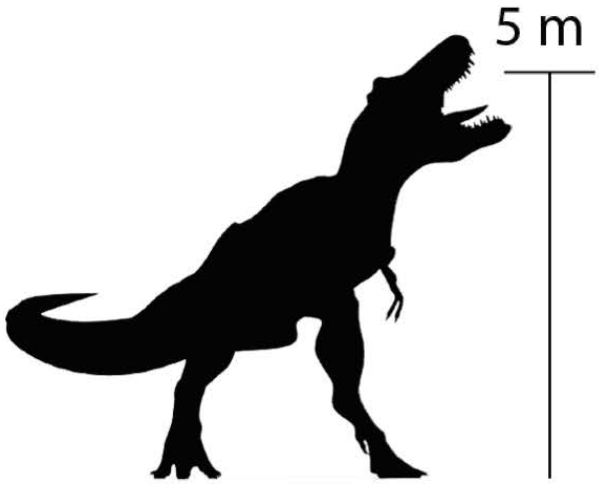
200,000 L of
purified water

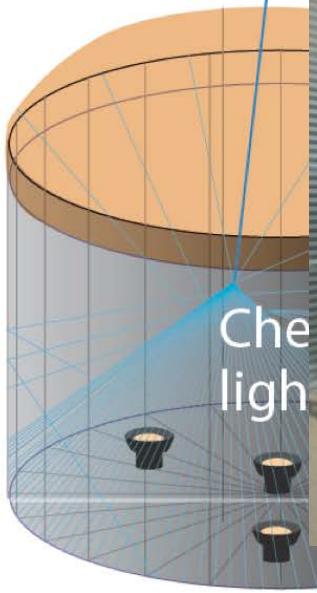
photomultiplier
tube (PMT)

HAWC Tanks


air shower particle
5 m
Cherenkov light
7.3 m
200,000 L of purified water
photomultiplier tube (PMT)

HAWC Tanks

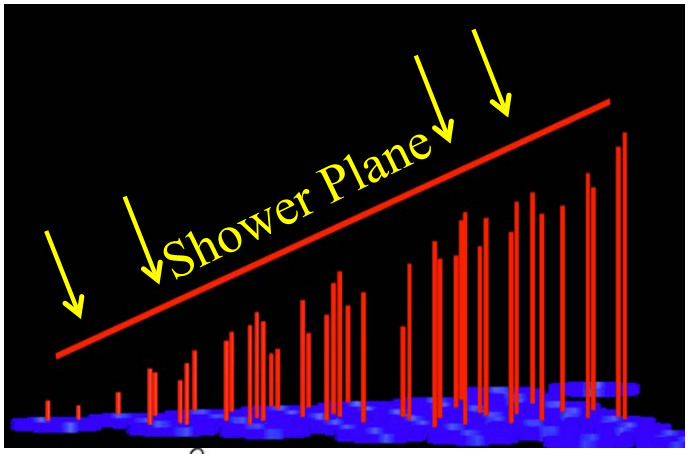


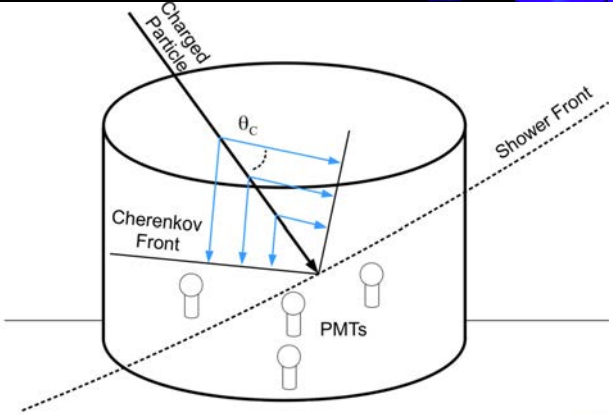



HAWC

HAWC

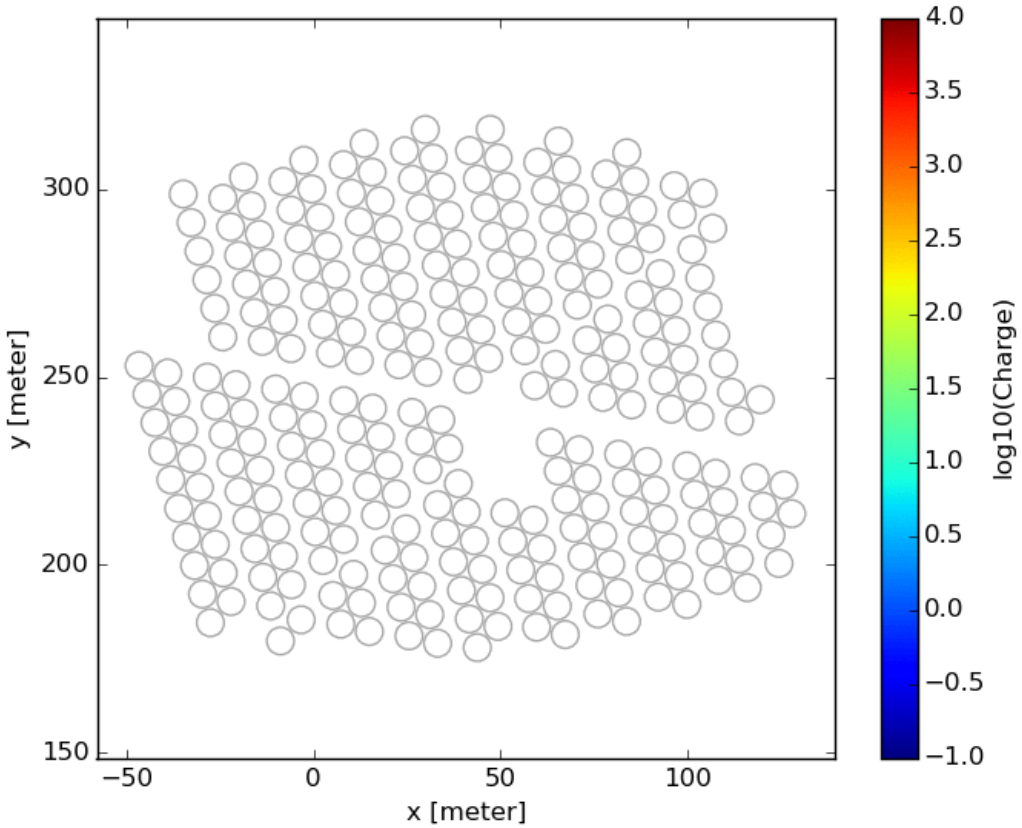
Angle Reconstruction Uses Timing



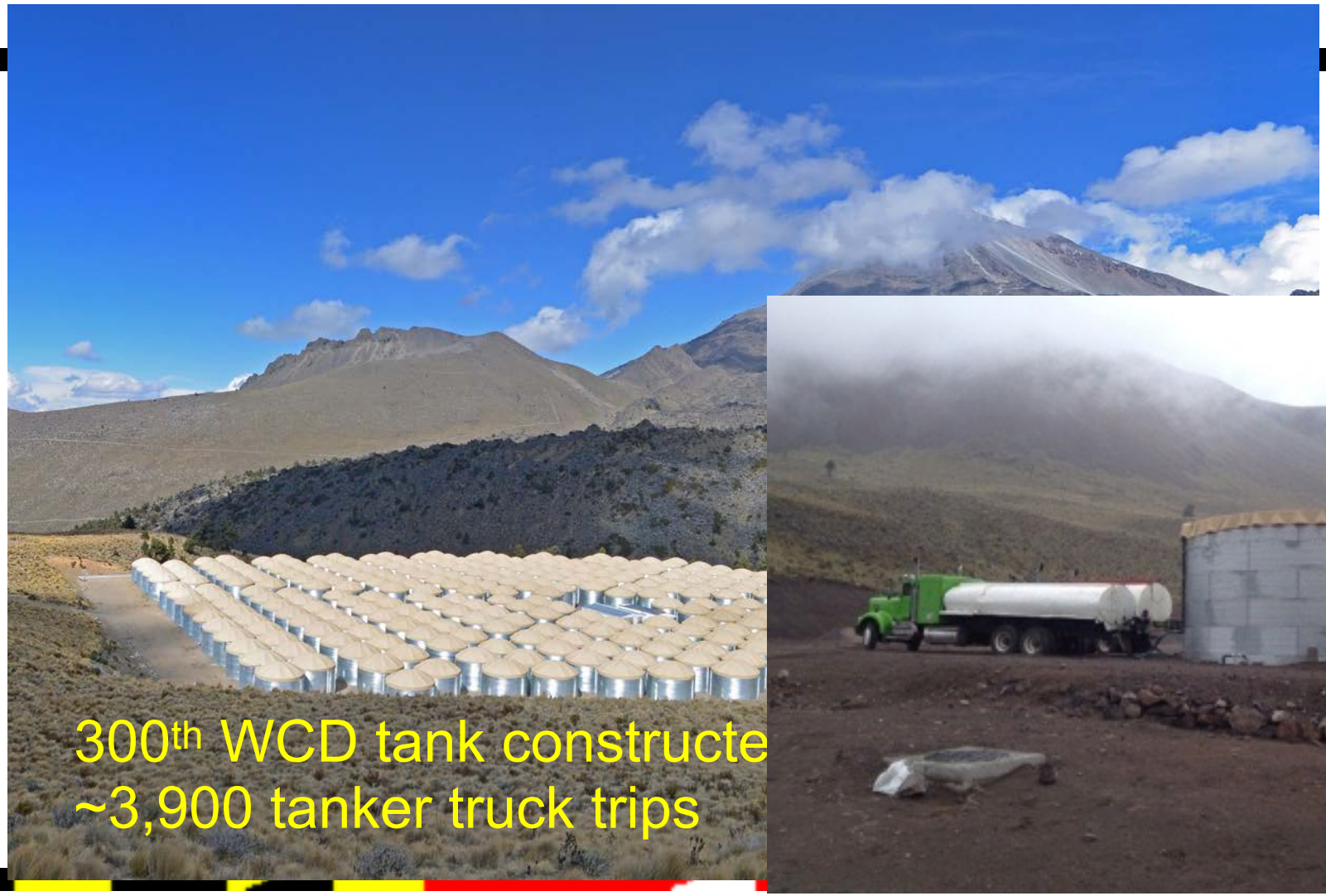


Photons convert to e+e- in the water

Angle Reconstruction Uses Timing




300th WCD tank constructed/filled Jan 2015
~3,900 tanker truck trips

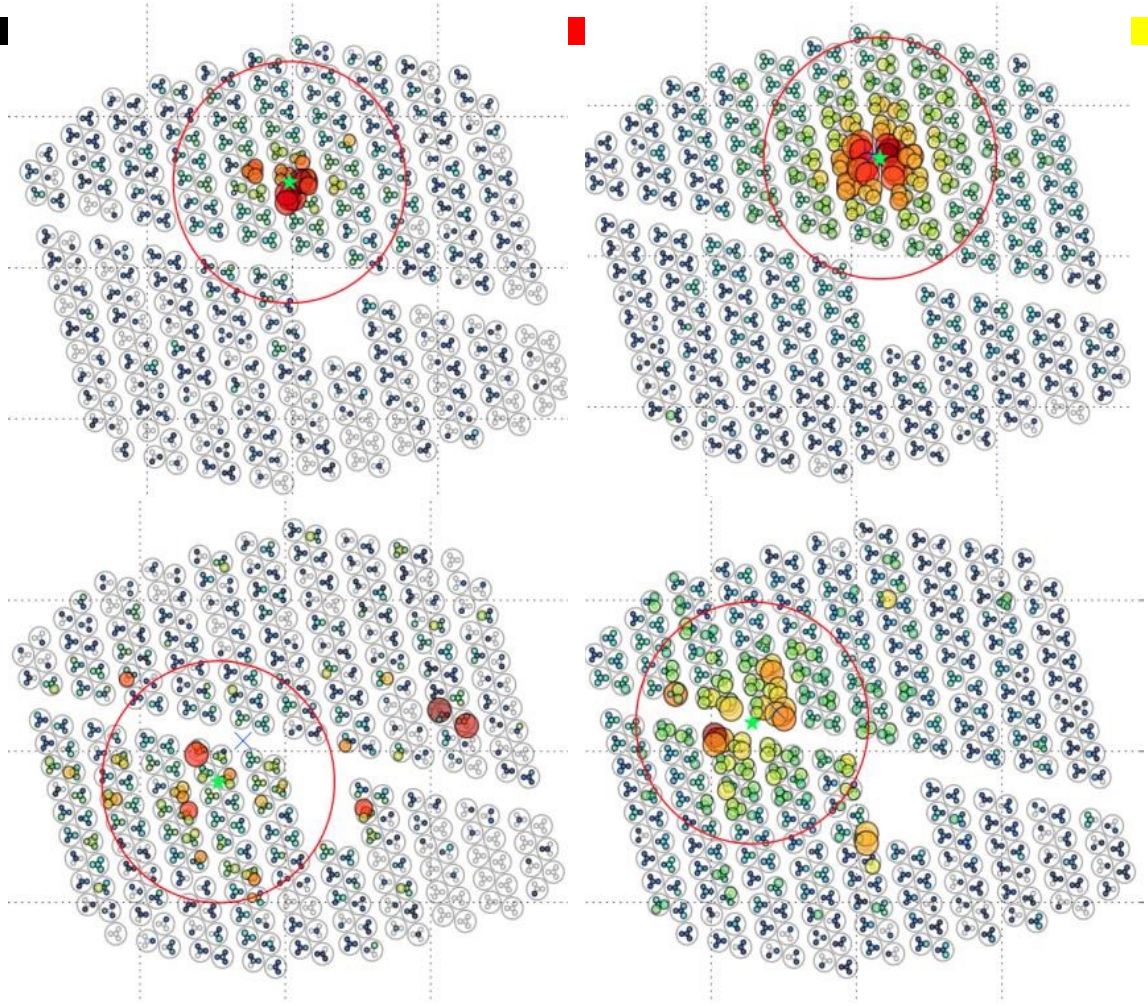

300th WCD tank constructe
~3,900 tanker truck trips

Gamma Hadron Separation (MC)

Gammas

Monte Carlo Simulation

Protons



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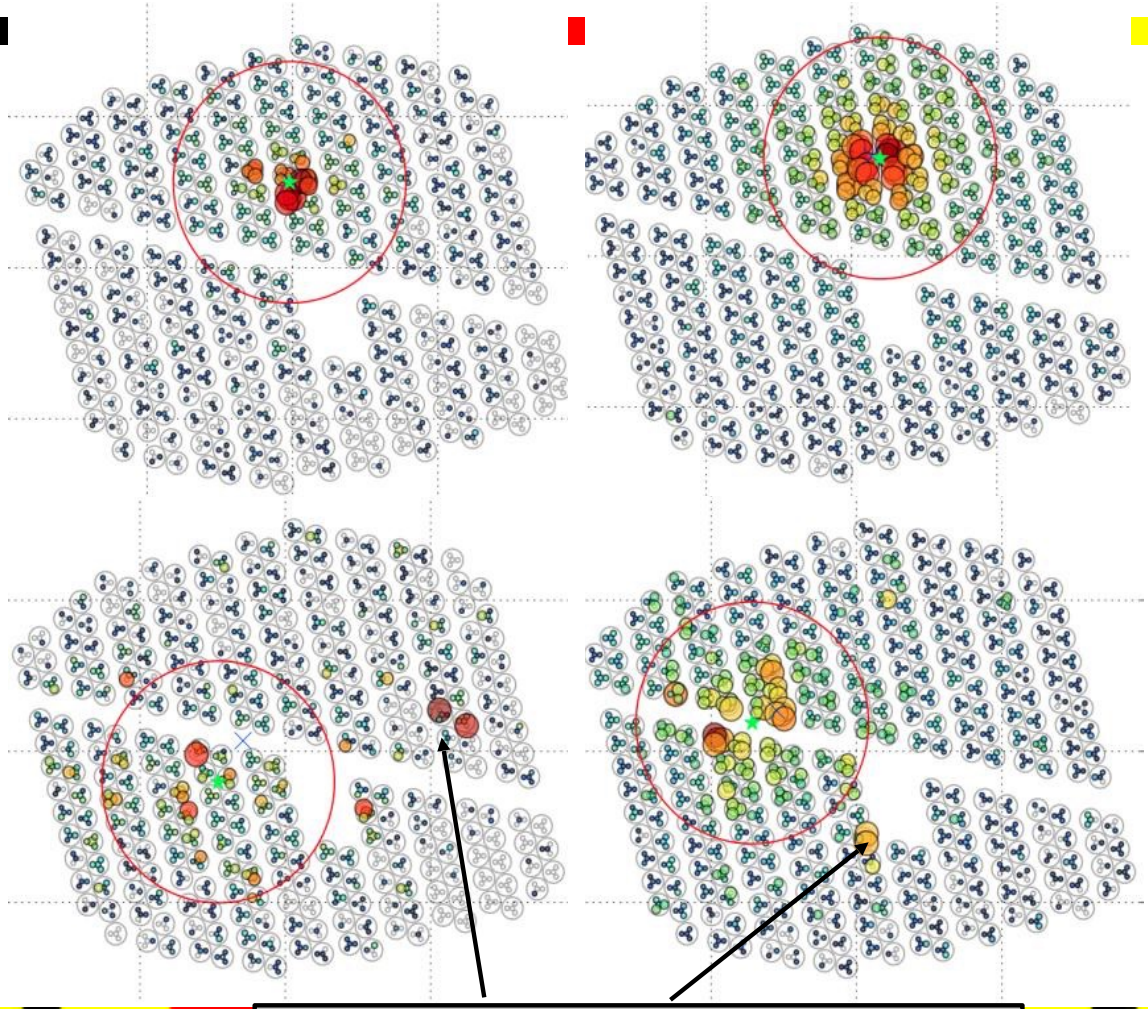
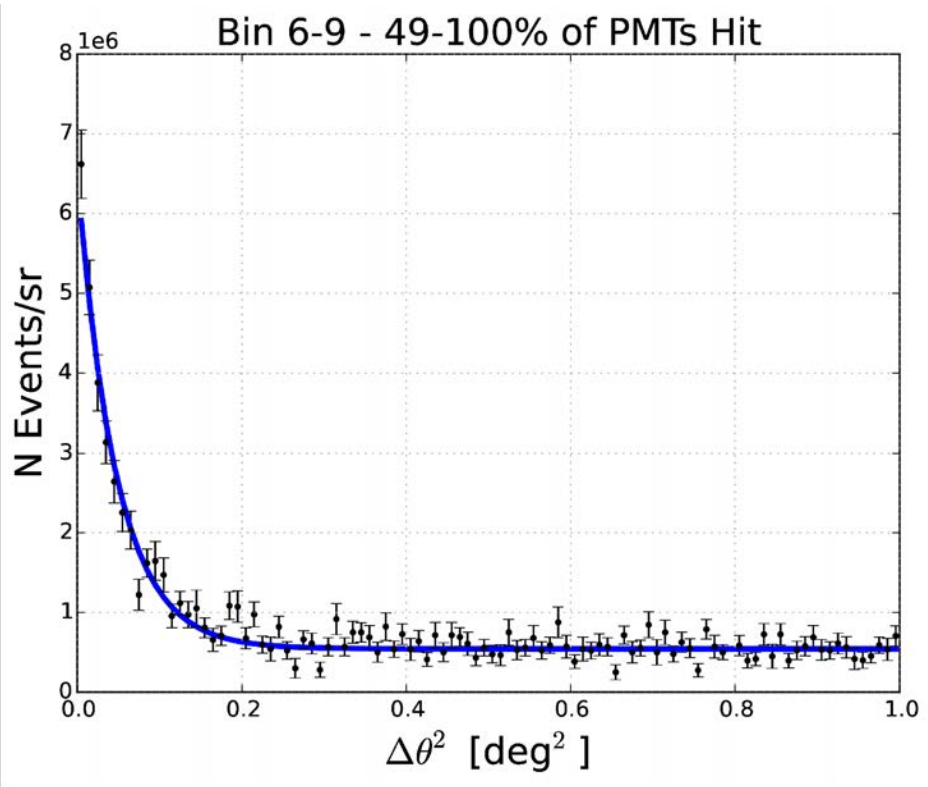
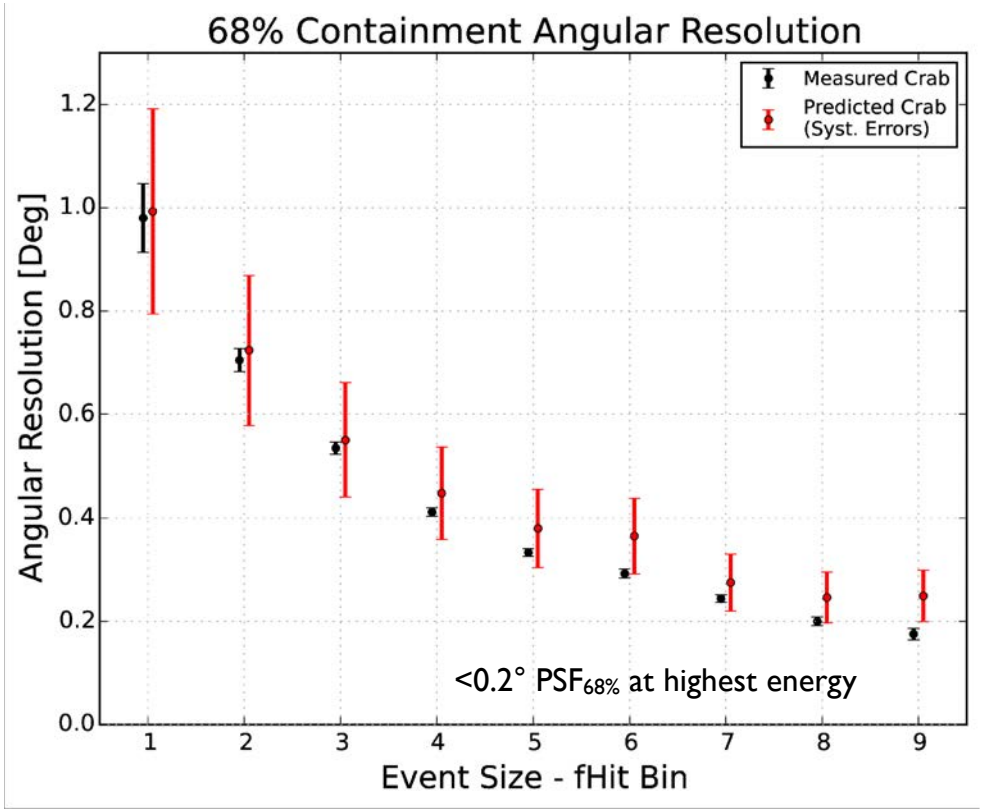


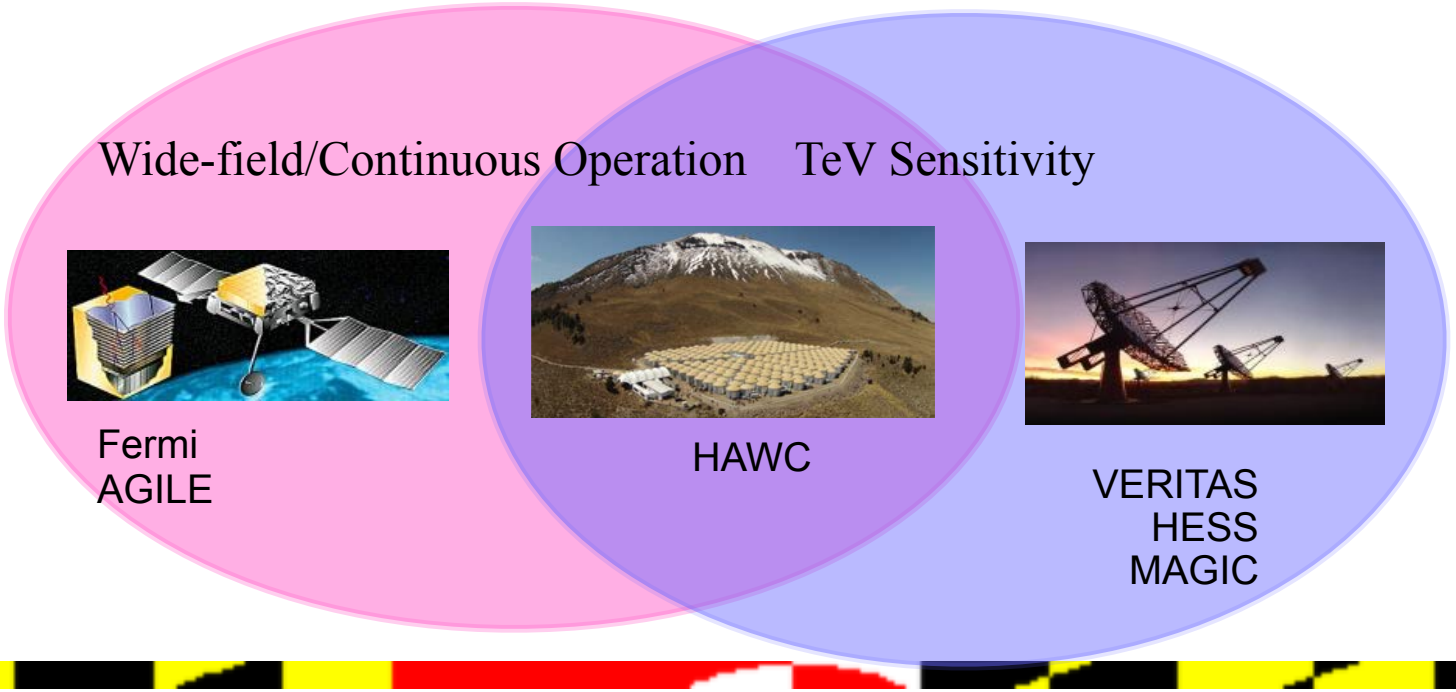
Angular Resolution



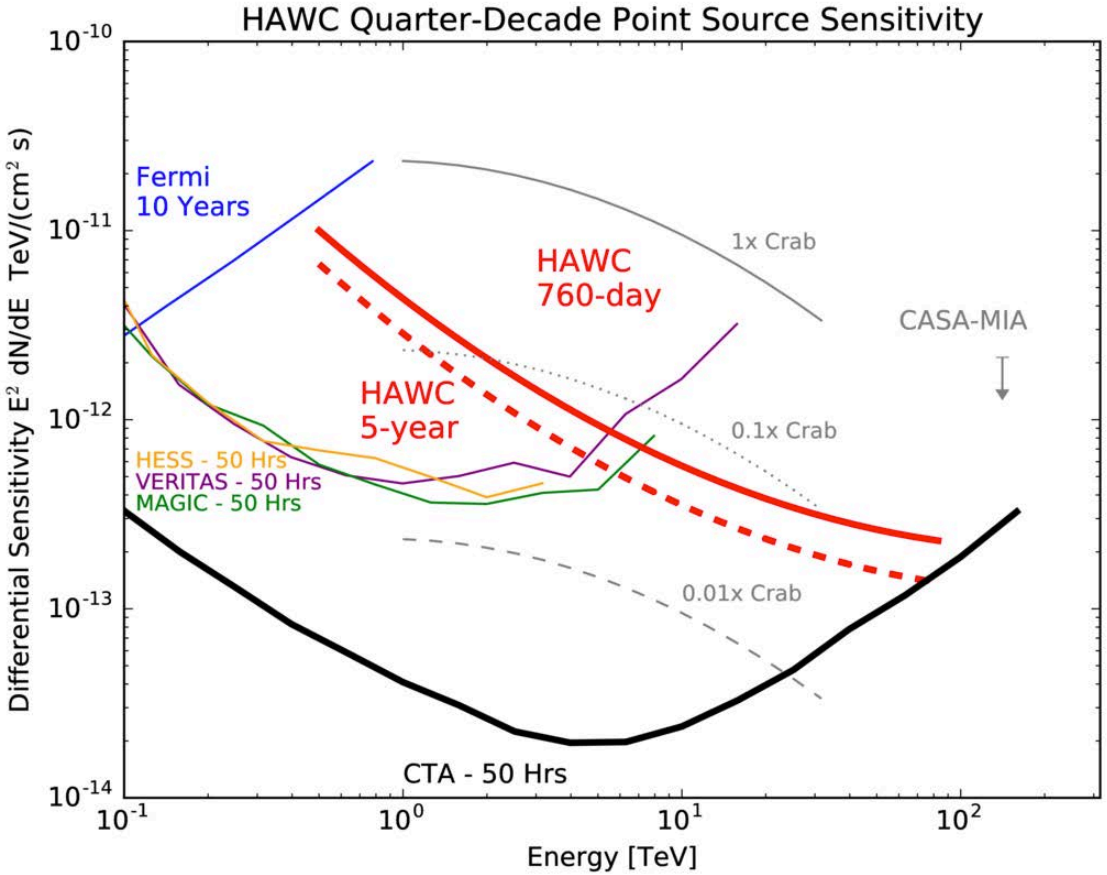


Complementarity of Gamma-Ray Detectors

- Space-based detectors - continuous full-sky coverage in GeV
- Ground-based detectors have TeV sensitivity
  - IACTs (pointed) excellent energy and angle resolution
  - HAWC has 24-hour >1/2 sky coverage



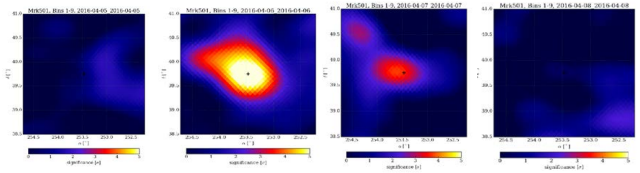
HAWC Differential Sensitivity

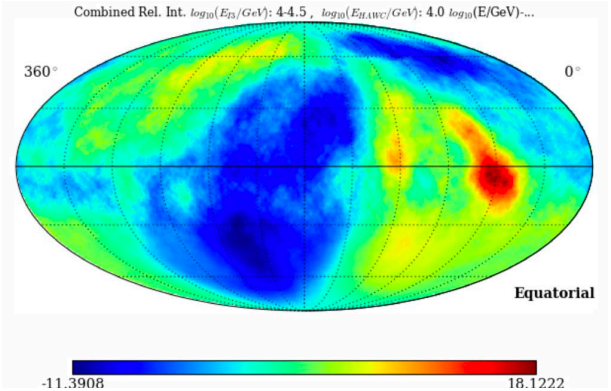


5 years of HAWC operations will give similar sensitivity at 10 TeV as 1 TeV for ACTs

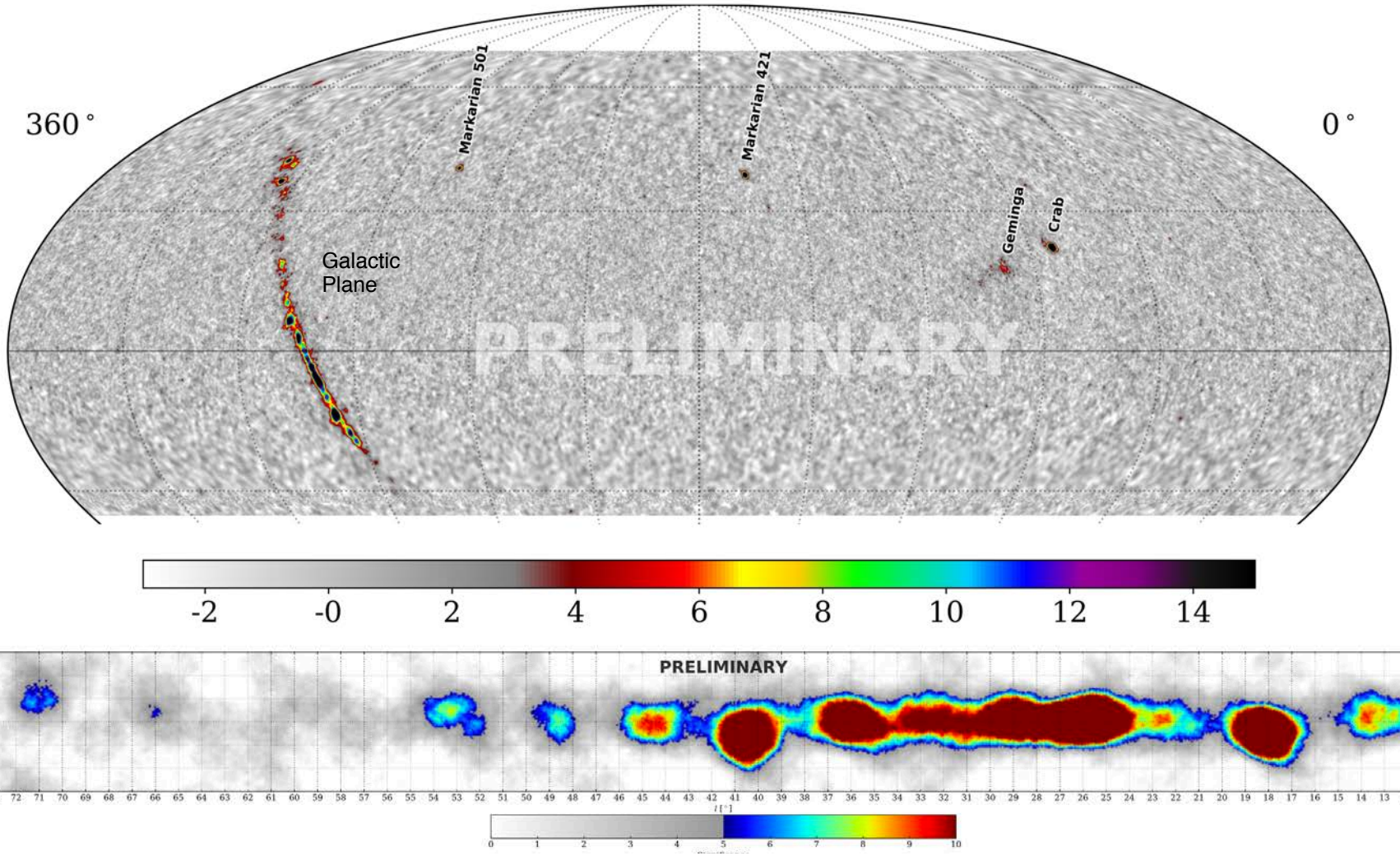
What can you do with a wide-field instrument?

- Gamma Ray Astrophysics
  - Galactic Gamma-Ray Sources - Survey
    - Discovery of Pulsars, PWNs, Binaries - especially extended sources
    - Study of high energy behavior - source of galactic cosmic rays
    - Morphology of sources
    - Galactic Diffuse and Fermi Bubbles
  - Transients
    - Gamma Ray Bursts - high energy behavior
    - AGN - Continuous monitoring
    - IceCube, LIGO multimessenger observations
- Particle Physics
  - Dark Matter - can look for places with no visible signal
  - Primordial Black Holes
  - Violations of Lorentz Invariance
  - Look for sources of positron excess
- Cosmic Ray Anisotropy

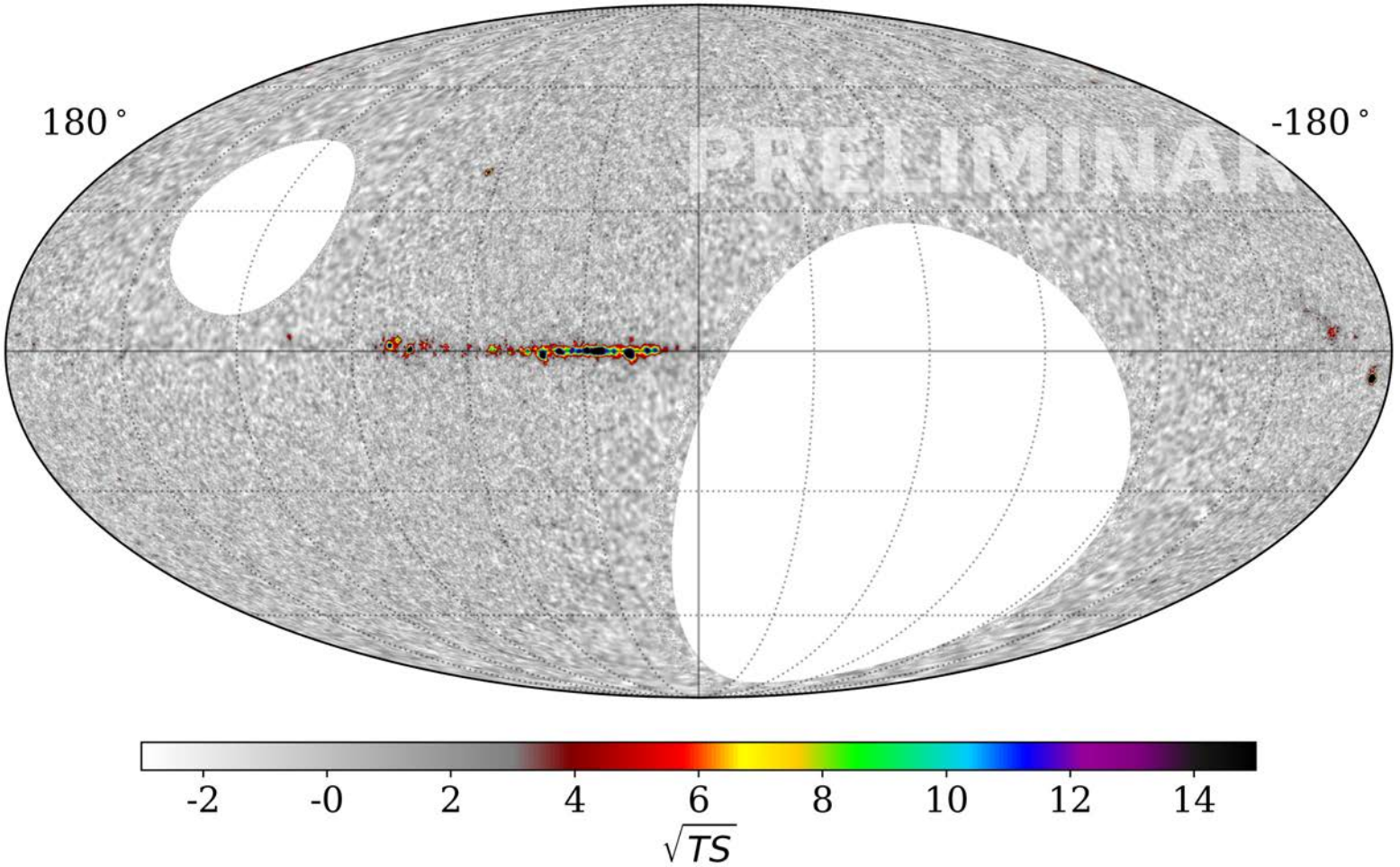




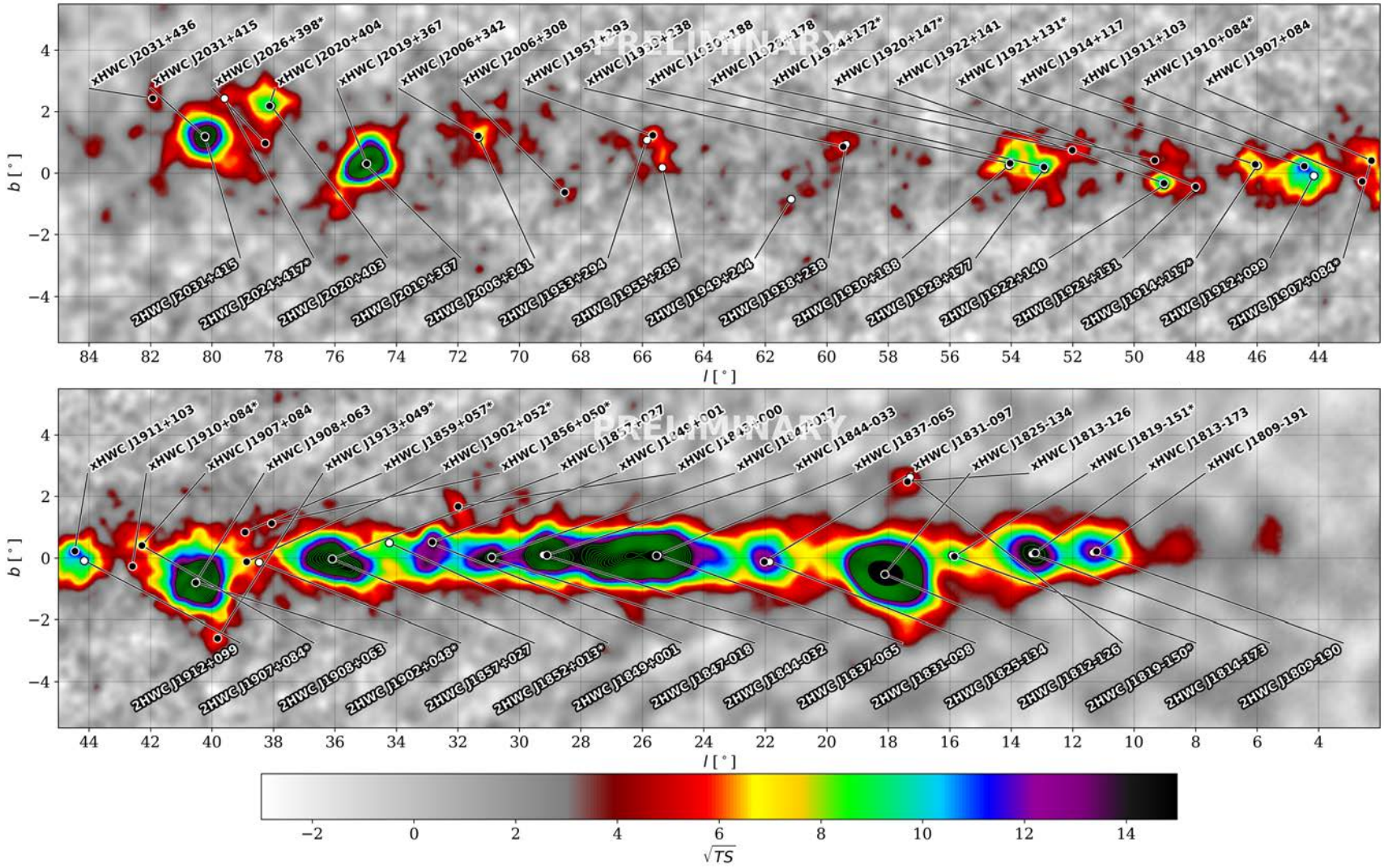
HAWC Sky Map 911 Days of Data

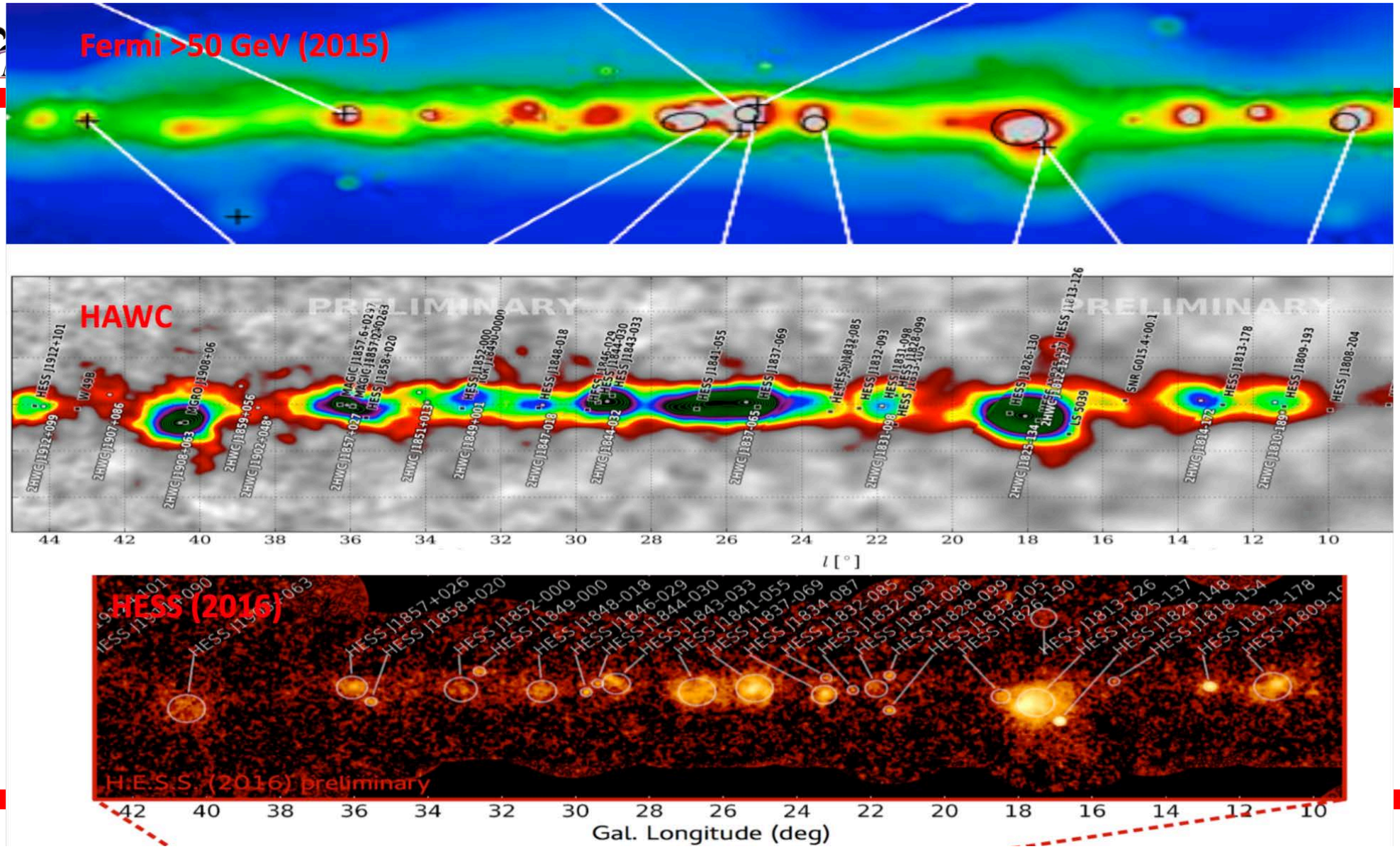


HAWC 911-Day TeV Sky Survey

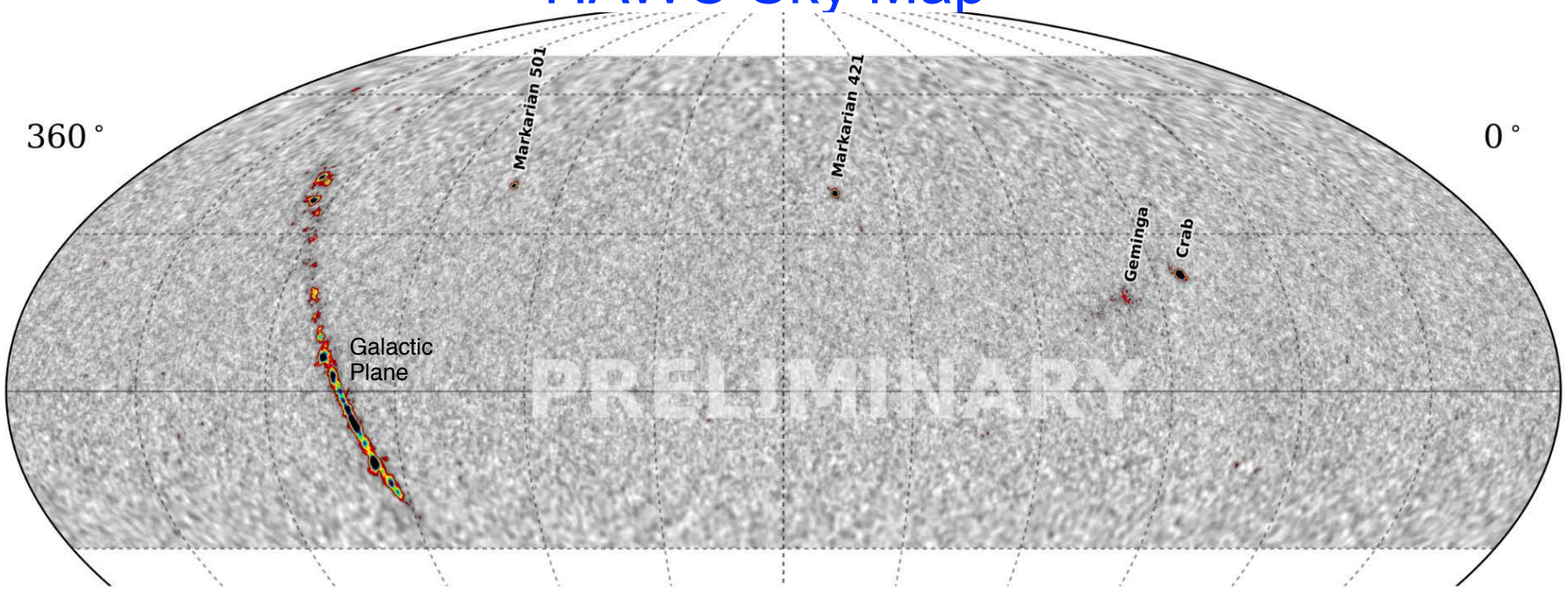


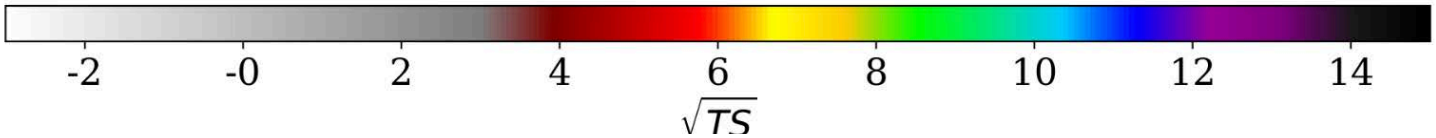
911 Days of Data

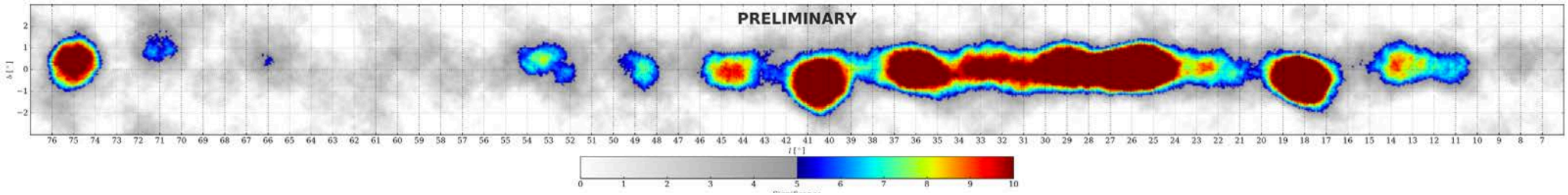



Fermi >50 GeV (2015)
HAWC
PRELIMINARY
PRELIMINARY
HESS J1912+101
W 49B
2HWC J1912+099
2HWC J1907+086
MGRO J1908+06
2HWC J1908+063
2HWC J1859+056
2HWC J1902+048*
MAGIC J1857.6+0237
MAGIC J1857.2+0263
HESS J1858+020
2HWC J1857+027
2HWC J1851+013*
HESS J1852-000
GeV J1849+0000
2HWC J1849+001
HESS J1848-018
2HWC J1847-018
HESS J1846-029
HESS J1844-030
HESS J1843-033
2HWC J1844-032
HESS J1841-055
2HWC J1837-065
HESS J1837-069
HESS J1834-087
HESS J1832-093
2HWC J1831-098
HESS J1831-098
HESS J1828-099
HESS J1826-130
2HWC J1825+134
HESS J1813-126
SNR G015.4+00.1
LS 5039
2HWC J1814-172
HESS J1813-178
2HWC J1810+189
HESS J1809-193
HESS J1808-204
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10
l [°]
HESS (2016)
H.E.S.S. (2016) preliminary
42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10
Gal. Longitude (deg)

HAWC Sky Map

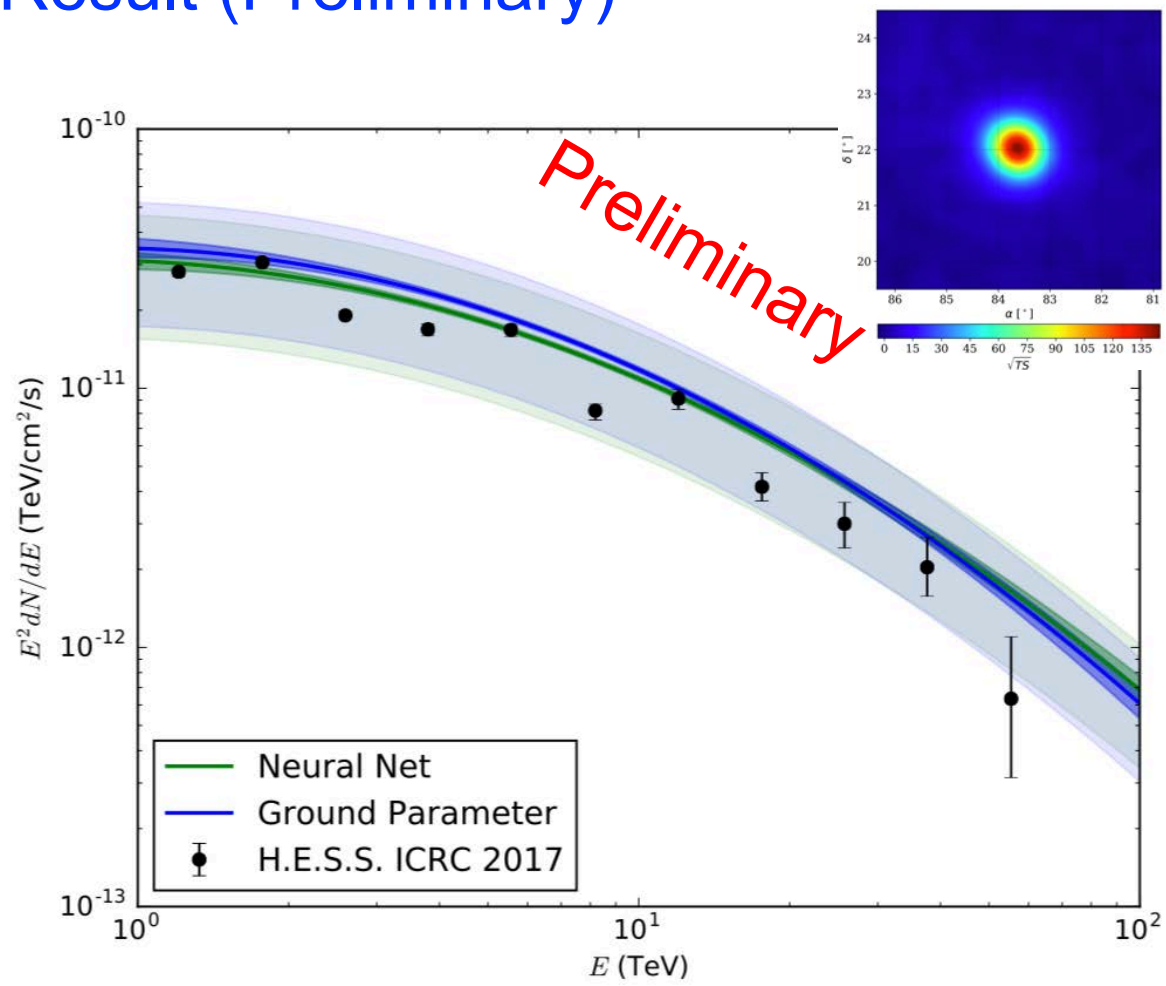

360 °
0 °
Markarian 501
Markarian 421
Geminga
Crab
Galactic
Plane
PRELIMINARY


-2
-0
2
4
6
8
10
12
14
$\sqrt{TS}$


PRELIMINARY

Crab Fit Result (Preliminary)

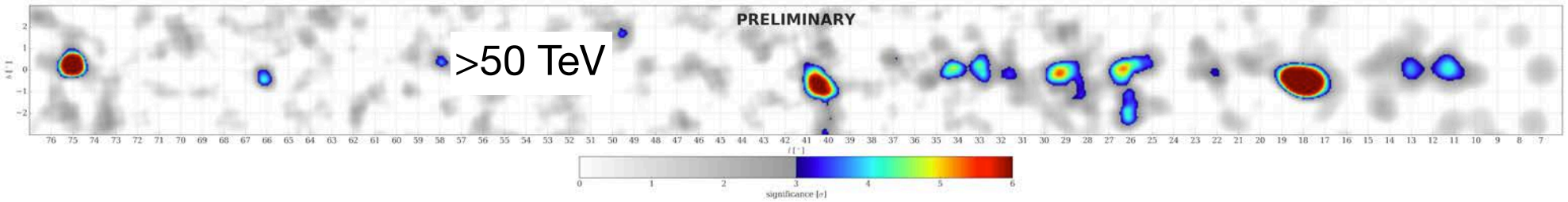
- Statistical errors using new energy variables are improved compared to published HAWC result[a].
- Systematics analysis in progress. Assuming 50% systematic from published HAWC Crab analysis, fits with new energy variables are compatible with H.E.S.S measurement.



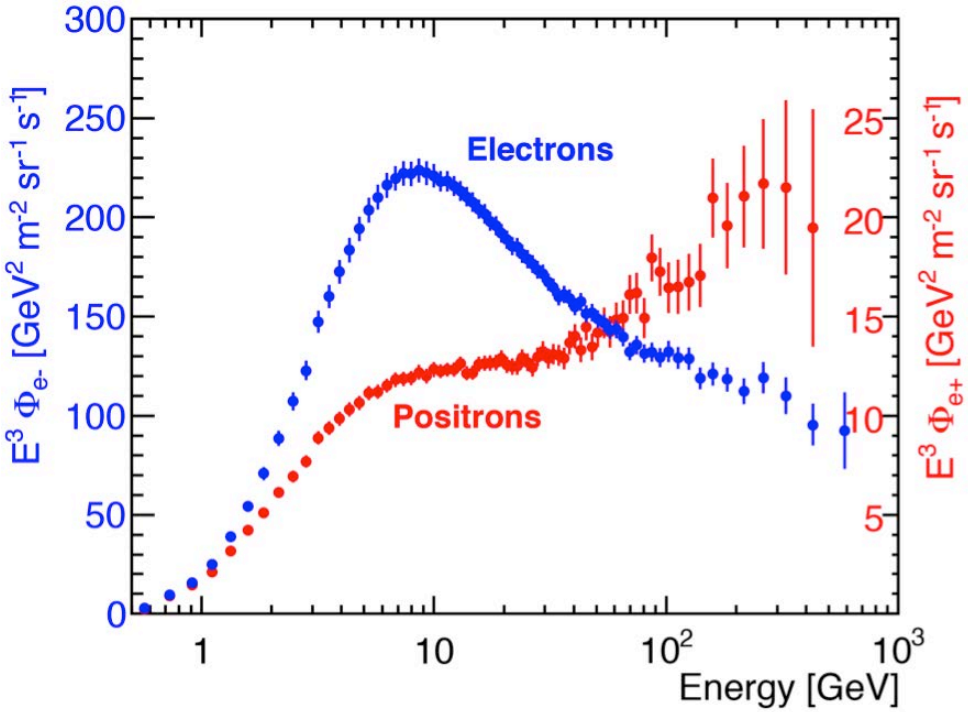
[a] https://arxiv.org/abs/1701.01778

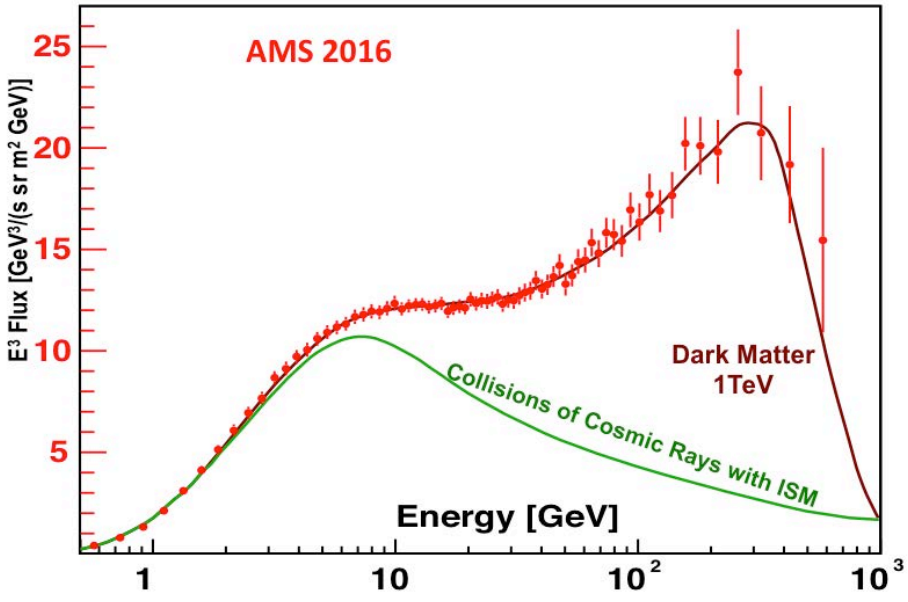
Highest Energy Sky

- By measuring spectra out beyond 30 TeV we can look for hadronic accelerators
- HAWC has produced the first map showing sources above 50 TeV
- Once we measure the spectra we can determine their origin



AMS/PAMELA Electron/Positron Excess

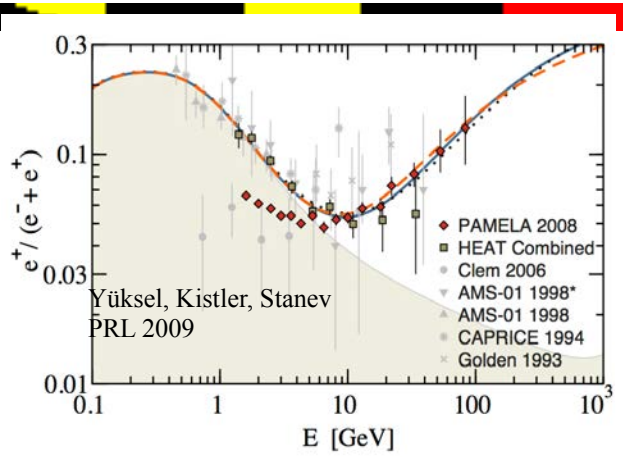


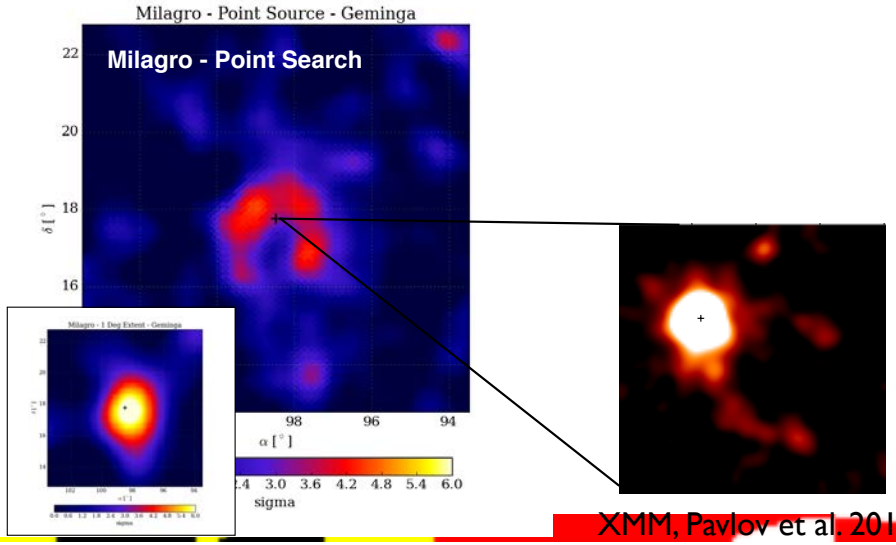


Evidence for Dark Matter?

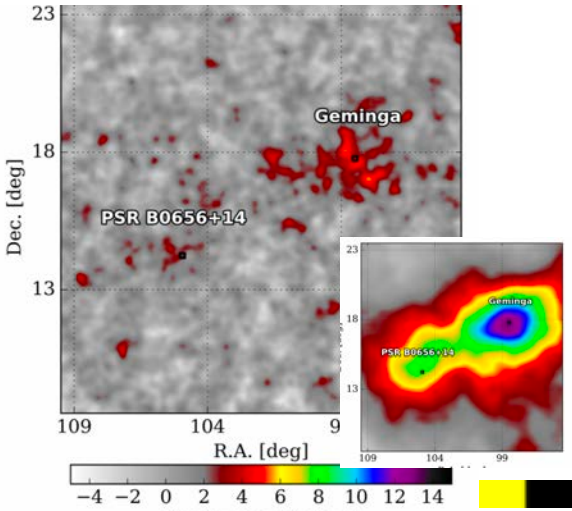
Pulsar Wind Nebulae - Geminga and PSR B0656+14

- Geminga is closest (250 psec) known middle aged (300ky) pulsar
- PSR B0656+14 (Mongogem) 300ps, 100ky
- Possible nearby cosmic ray acceleration site
  — explanation for positron excess (Yuksel et al. 2009)
- Not seen by IACTs, extent larger than IACT FOV



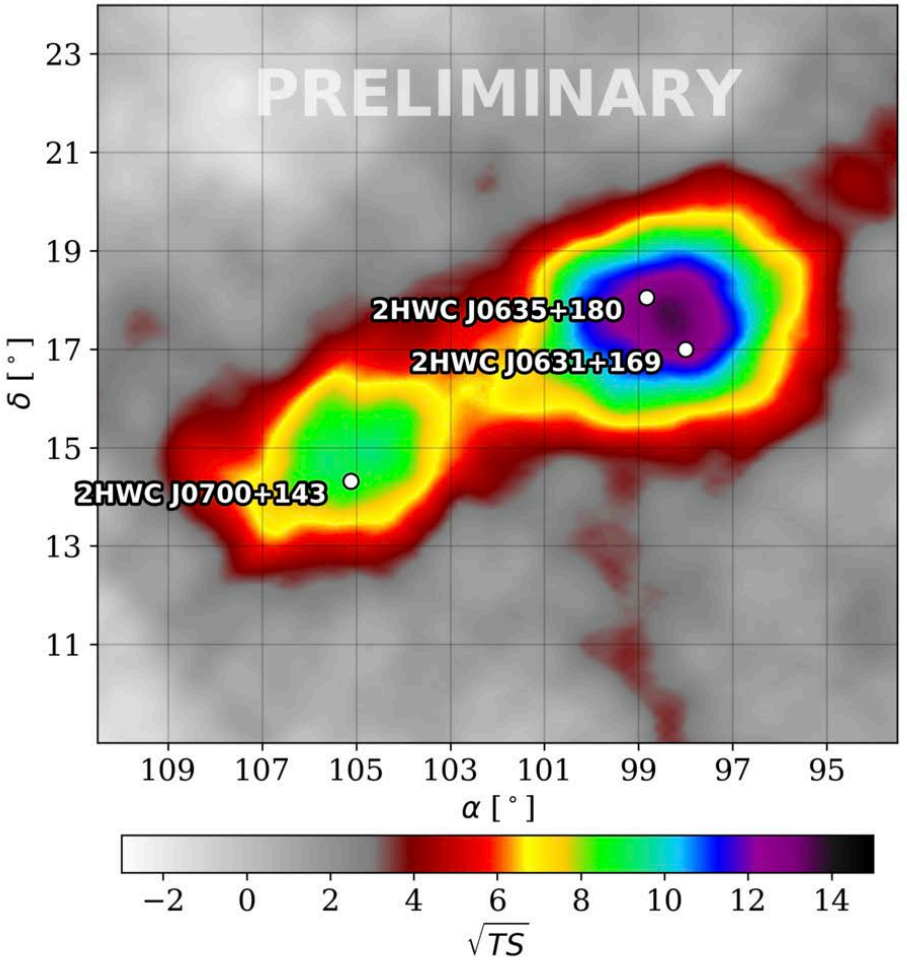


XMM, Pavlov et al. 2010

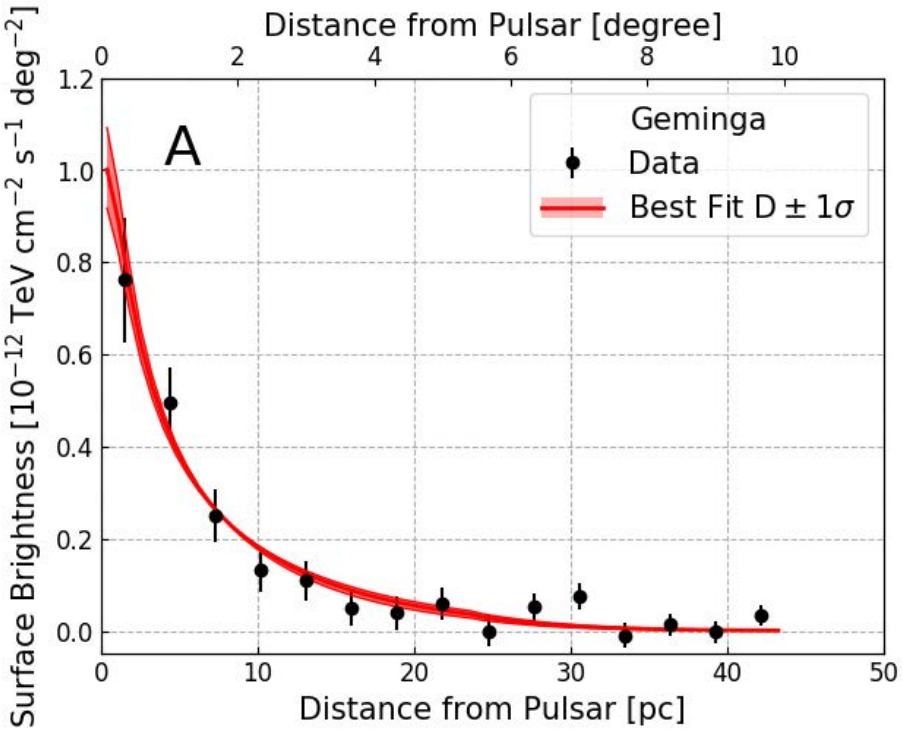


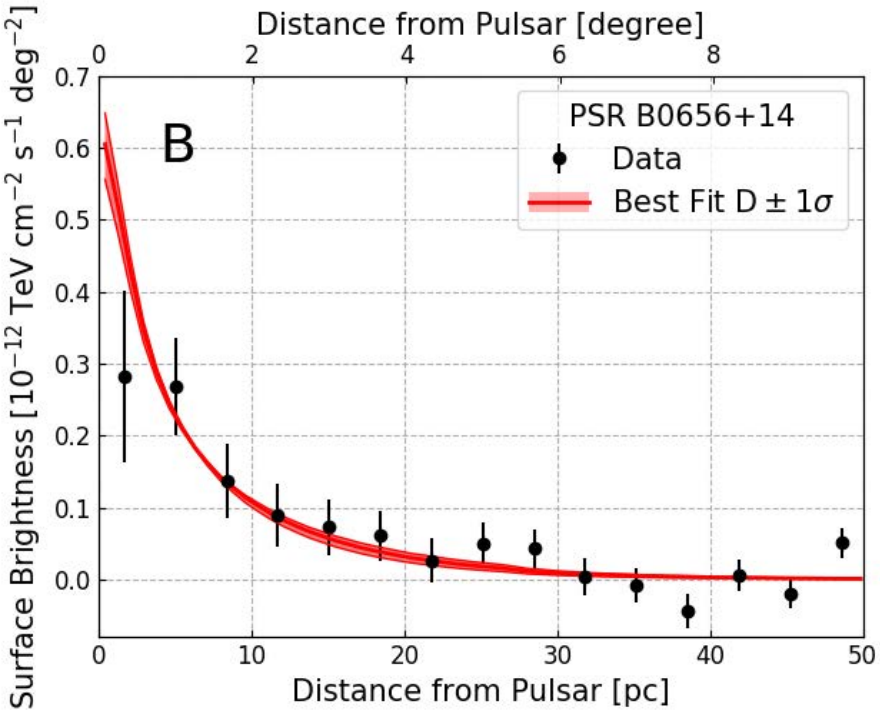
Geminga and PSR B0656+14 760 day data

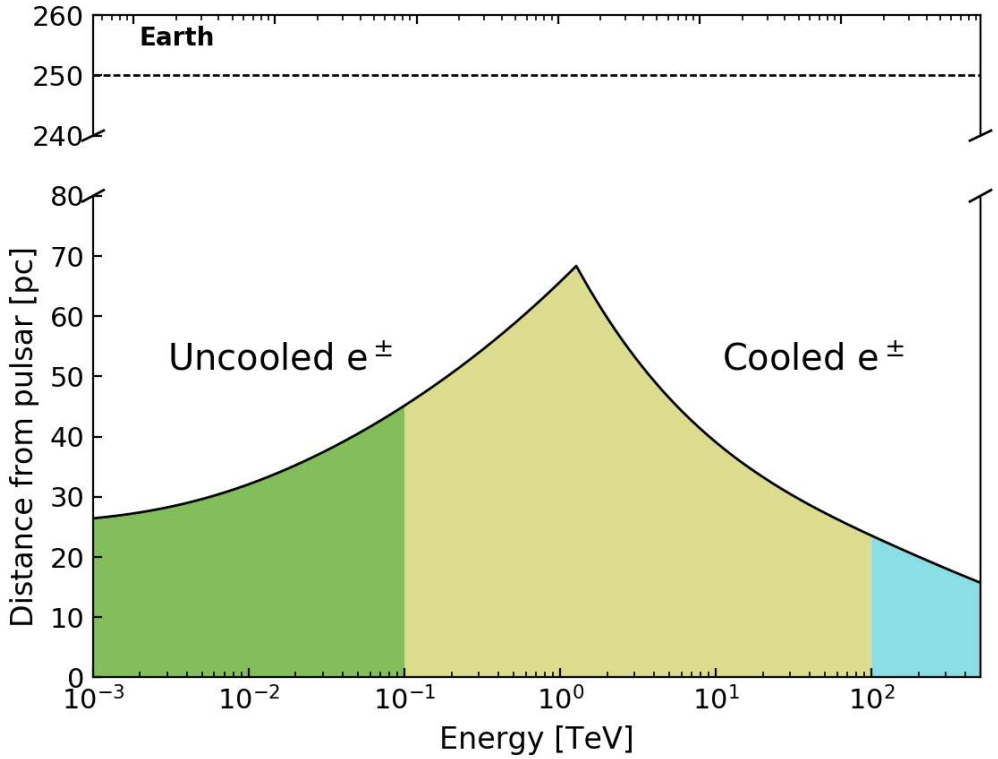
- PSR B0656+14 - similar age and distance as Geminga
- Gamma's above 20 TeV
  - These come from 100 TeV electrons
  - This is much bigger than the x-ray PWN
  - Fitting the radial distribution will allow us to measure the diffusion coefficient at high energies
- This can tell us if these are a source of local positrons seen by AMS and others

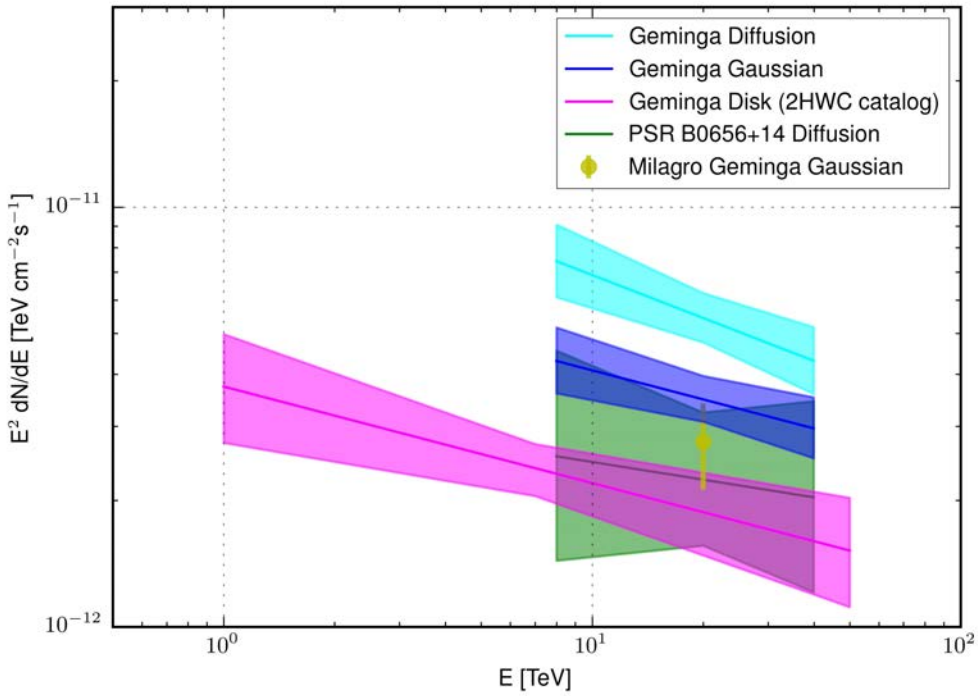


Radial Distribution

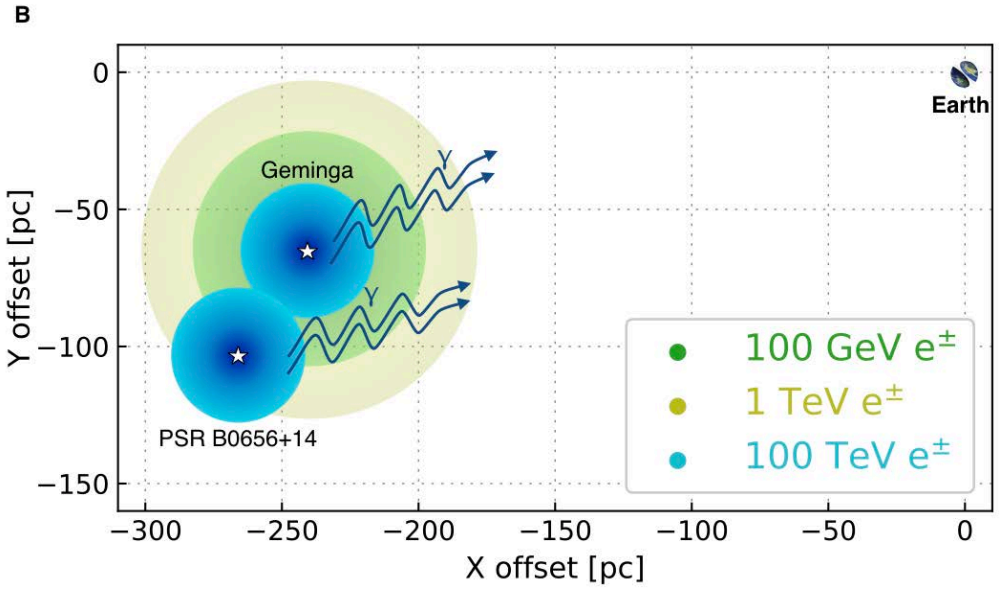


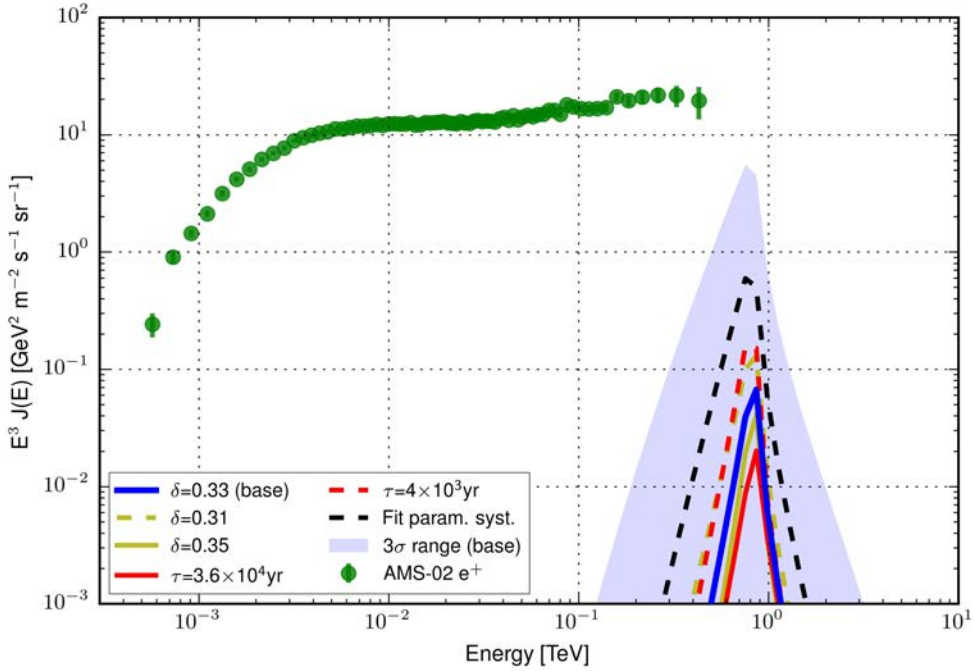



Earth
Uncooled e ±
Cooled e ±
Distance from pulsar [pc]
Energy [TeV]

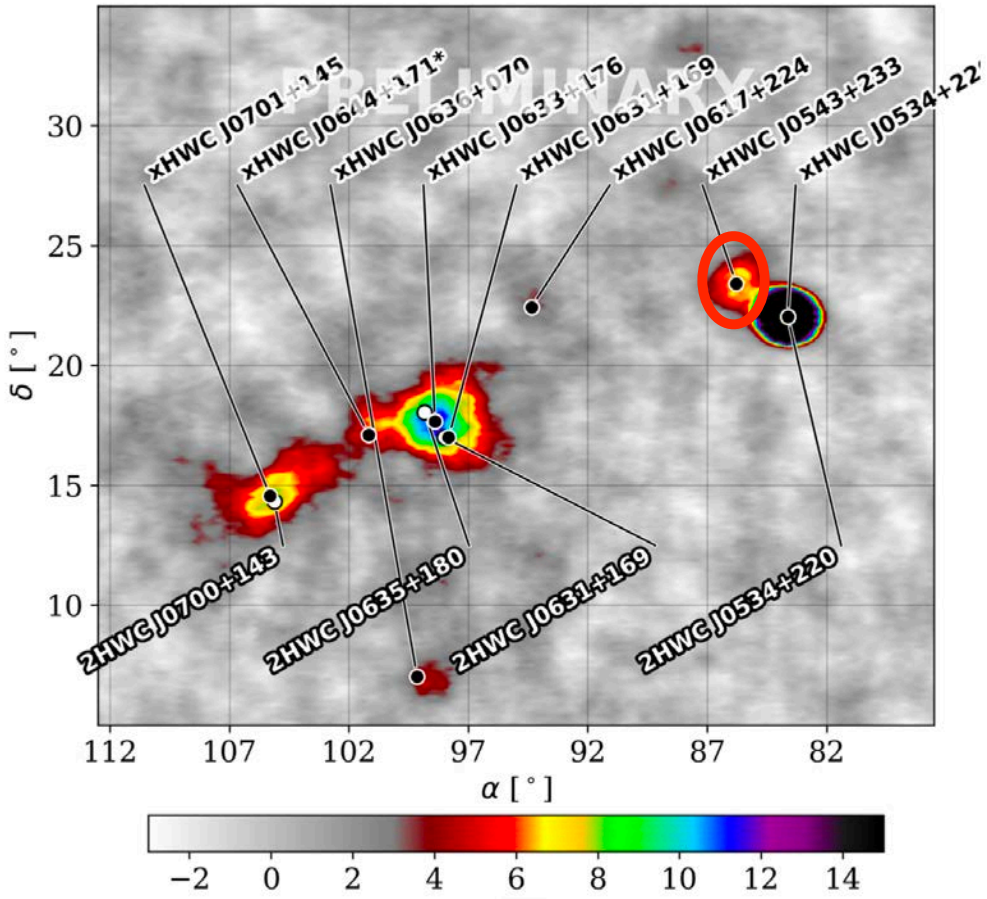

Geminga Diffusion
Geminga Gaussian
Geminga Disk (2HWC catalog)
PSR B0656+14 Diffusion
Milagro Geminga Gaussian
E² dN/dE [TeV cm⁻²s⁻¹]
E [TeV]

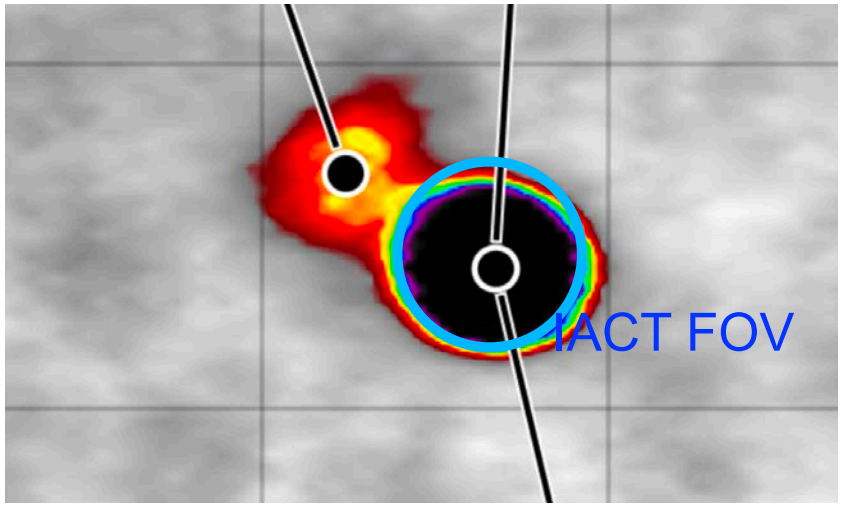
Unlikely Source of Positron Excess





Another - Hiding in Plain Sight J0543+233

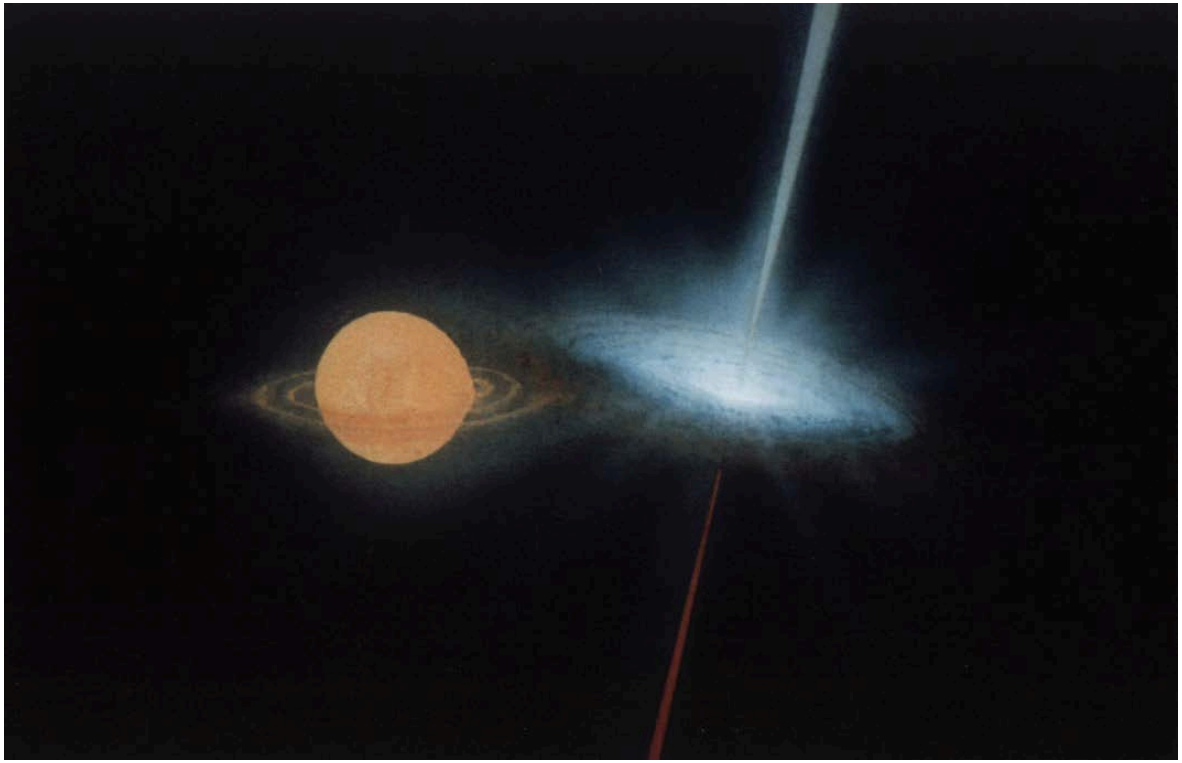




Another middle age PWN
similar to Geminga and B0656+14
$\dot{E} = 4.1 \times 10^{34}$ erg s−1,
d = 1.56 kpc, τ = 253 kyr

Can test if all are Geminga-like

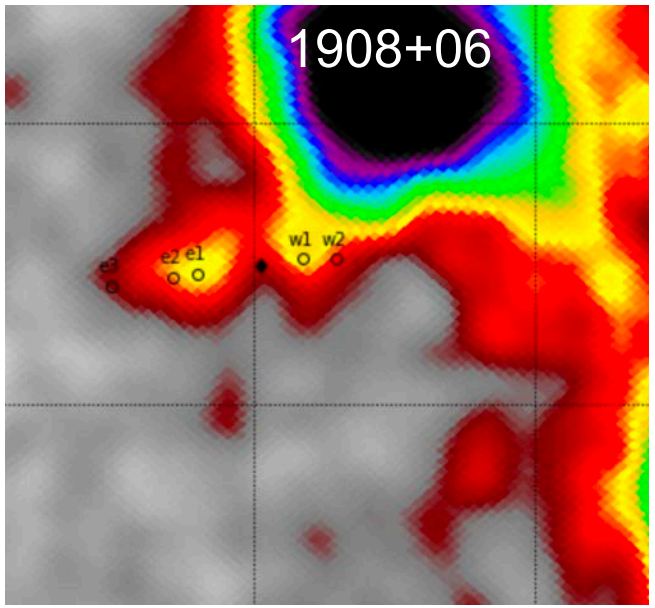
Microquasar SS433



Possible an A-type supergiant and a very extended disk around a black hole.
The jets from SS 433 precess with a period of 13 days.

Possible Detection of μ-quasar SS433

- SS433 - x-ray binary with black hole
- Imaged jets ~ perpendicular to line of sight & containing hadrons
- Until now, no jets have been imaged at TeV energies.
- SS 433 has long been a suspected VHE gamma-ray source.
- The observation of TeV lobes provides new information about SS 433, including its luminosity and magnetic field.



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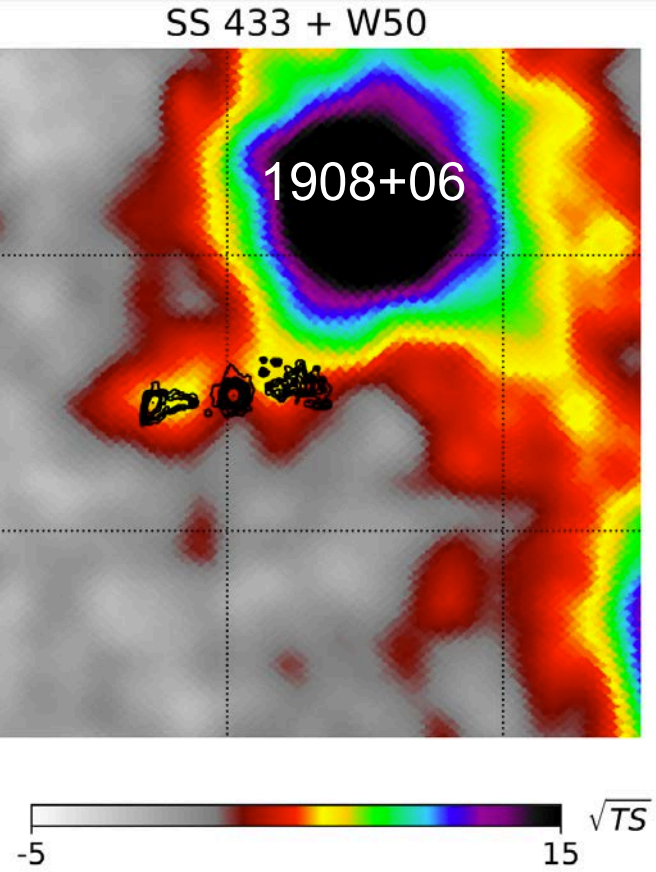
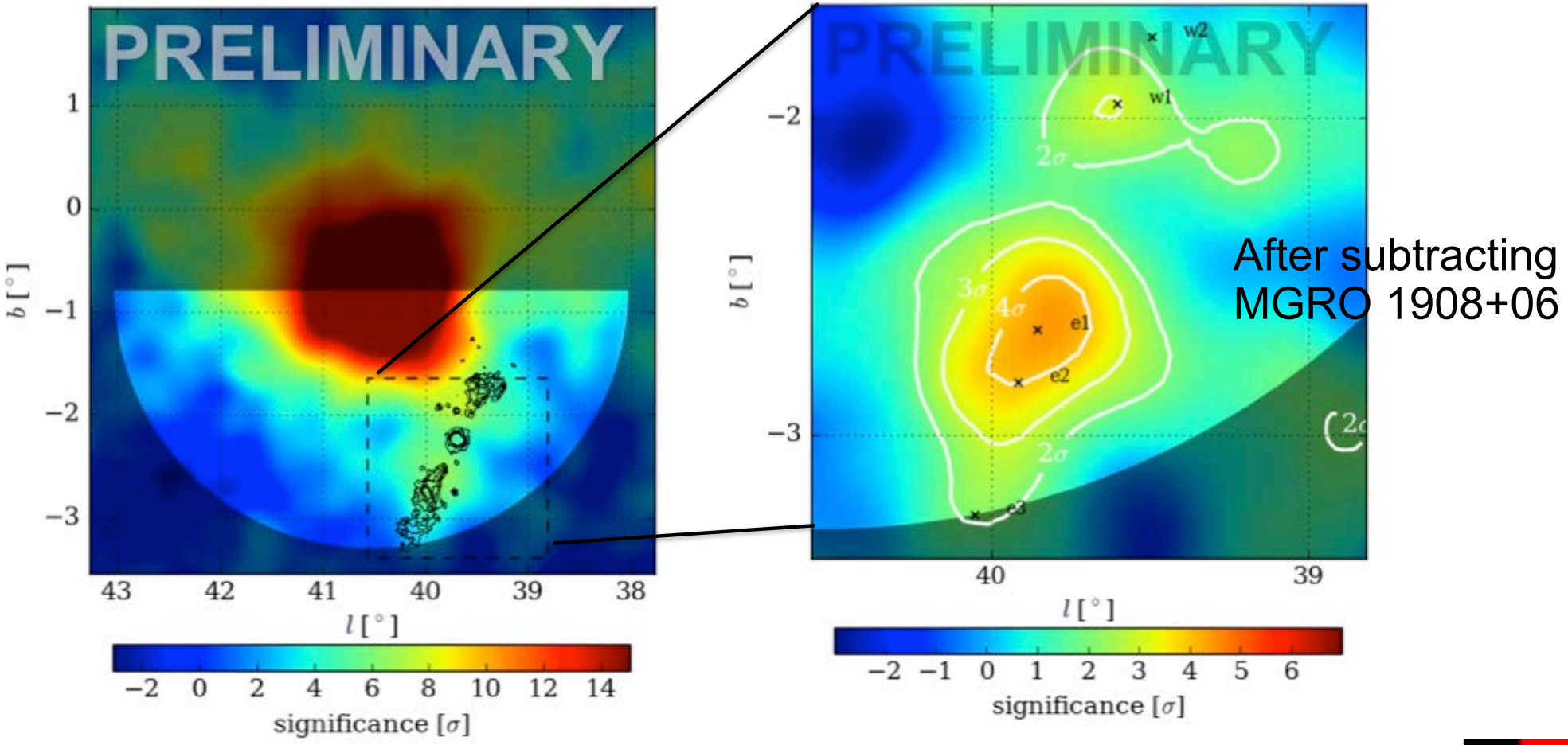


Possible Detection of μ-quasar SS433



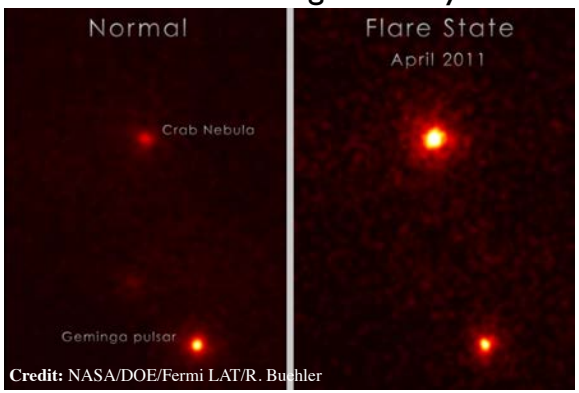
Possible Detection of μ-quasar SS433

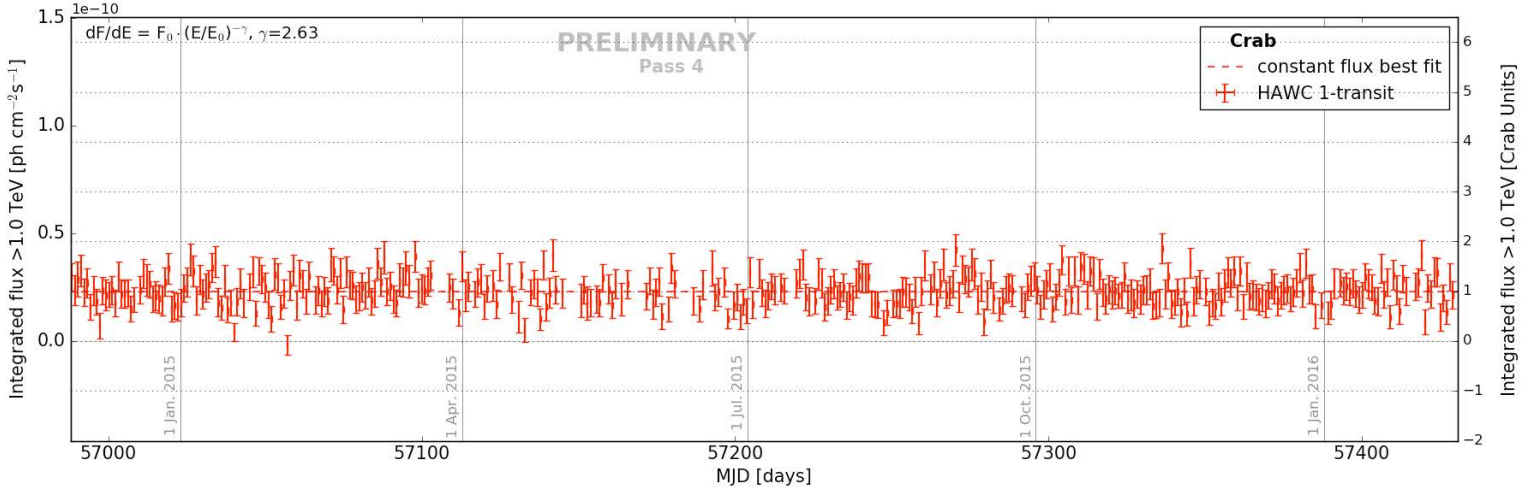
- We used a diffusion model to fit the extended MGRO J1908+06. We have also tested the Gaussian model and the powerlaw model and their effects on the fitted lobes have been included in the systematics (< 20%).
- For the spectral model, simple power law was used.
- Modeling can indicate whether the gammas are likely of hadronic or leptonic origin and where the acceleration occurs
- (Paper in progress)

Transient Search - The Crab Nebula

- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.
- HAWC Pass 4 data from Nov 26 2014 to June 2016.
- >105σ in 315 transits.
- Lightcurve binned in sidereal day.
- Consistent with constant flux.

MeV-GeV gamma ray

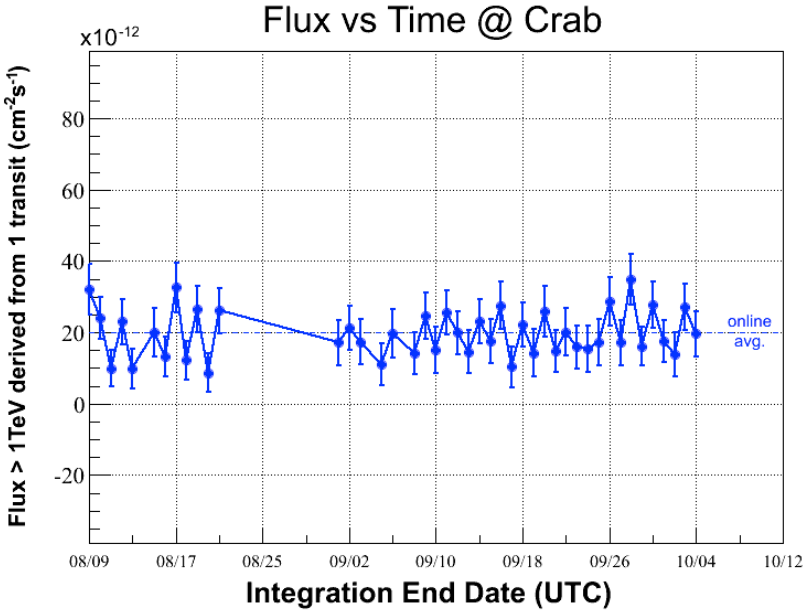


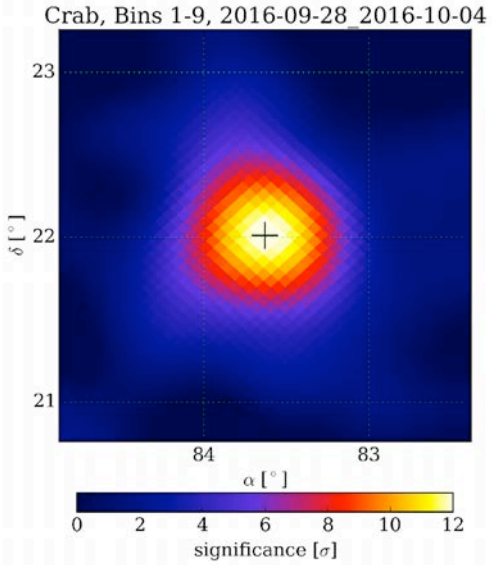


Transient Search - The Crab Nebula

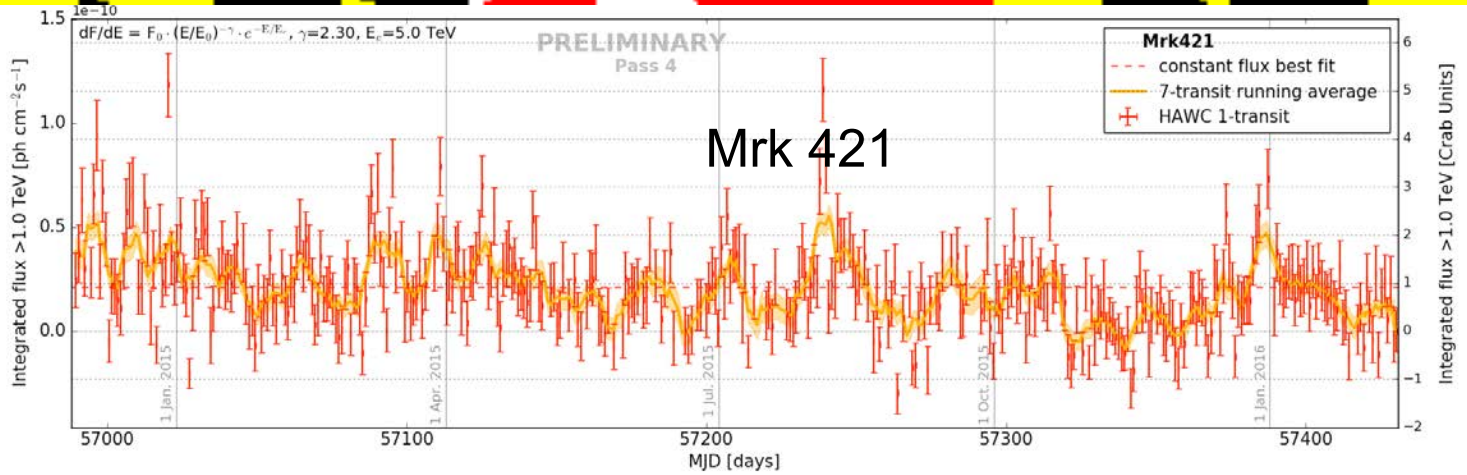
On October 3rd, 2016, AGILE (GeV) reported enhanced emission from the Crab Nebula (ATEL #9586). The Fermi-LAT *GeV) confirmed the detection in ATEL #9588, with flux up to 1.8 times larger than typical.

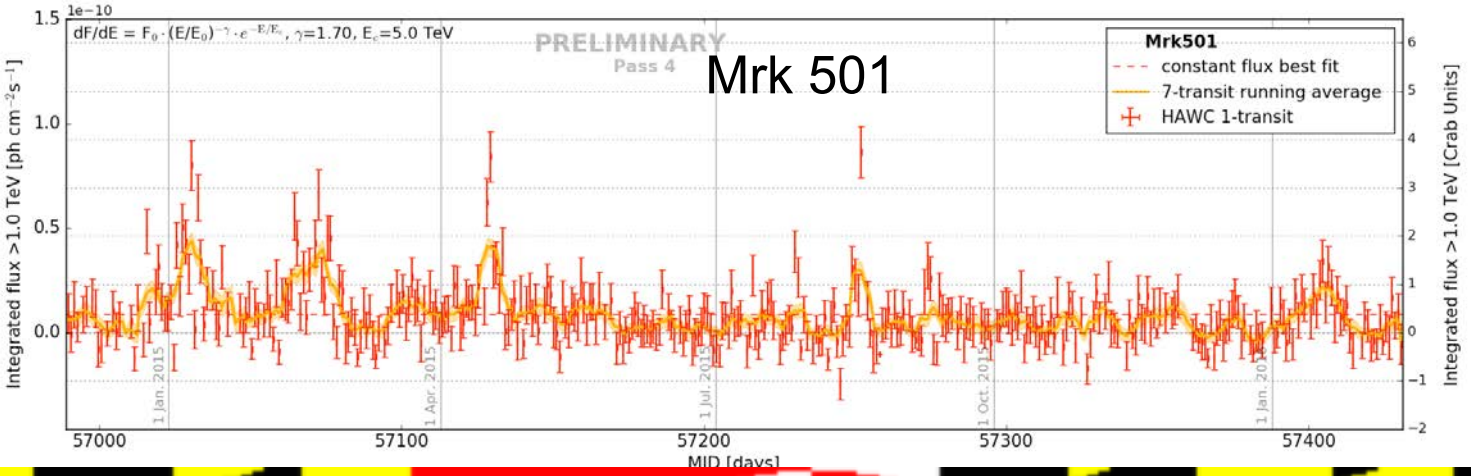
HAWC online monitoring shows the Crab to be fully consistent with its usual expectation over the same time period in the TeV.





Transient Search - Mrk 421 / Mrk 501



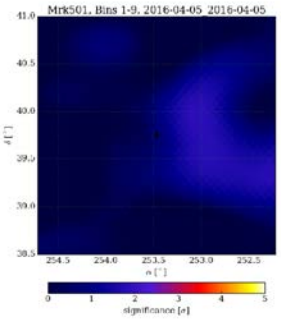


Transient Search - Mrk 501

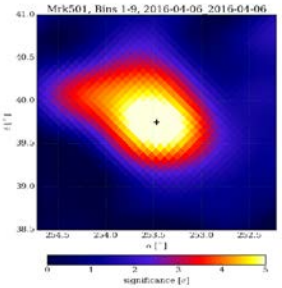
HAWC detection of increased TeV flux state for Markarian 501

ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT

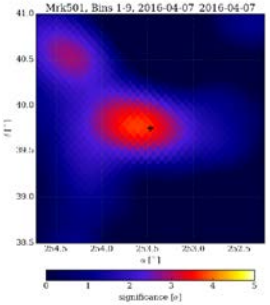
Astronomer's Telegram to immediately alert community of activity.



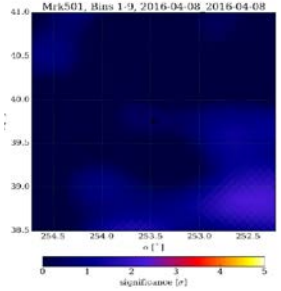
April 5, 2016



April 6, 2016



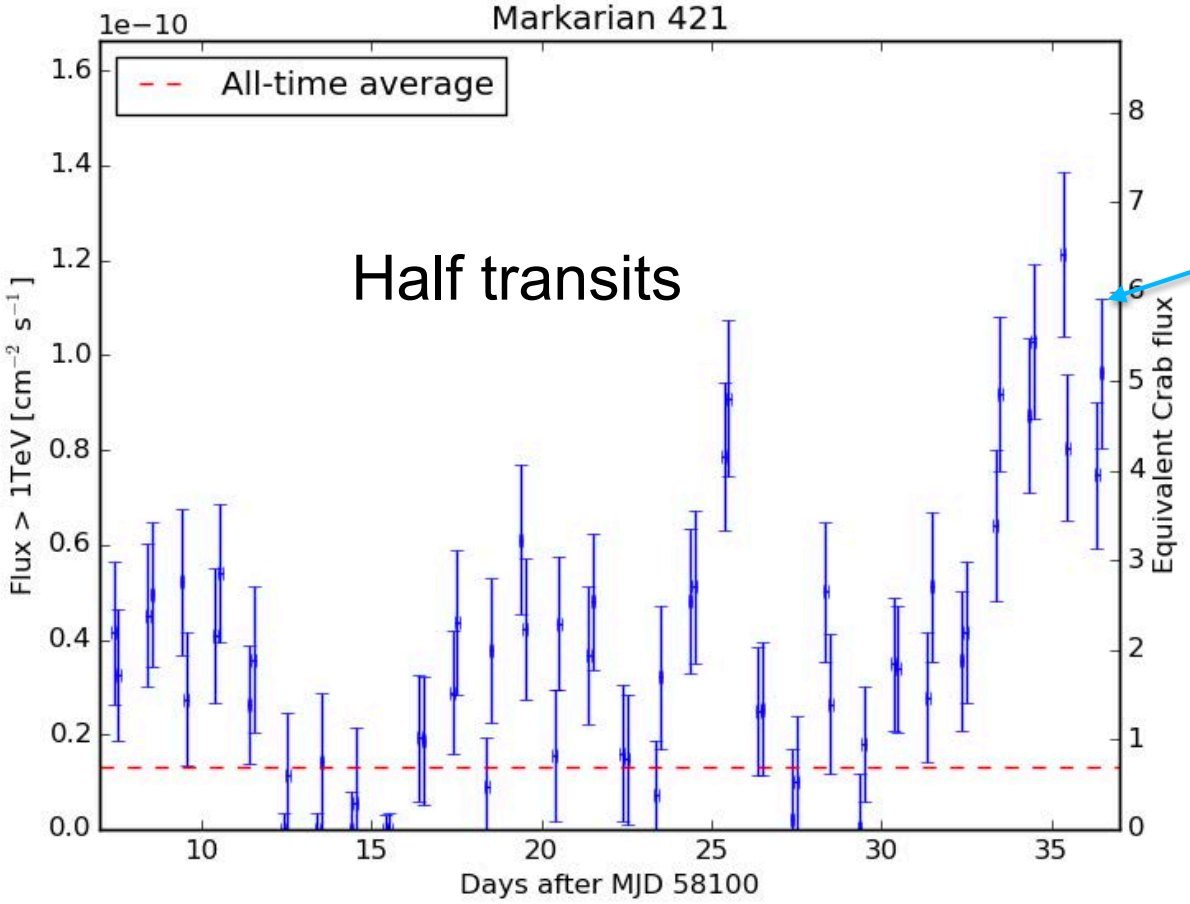
April 7, 2016



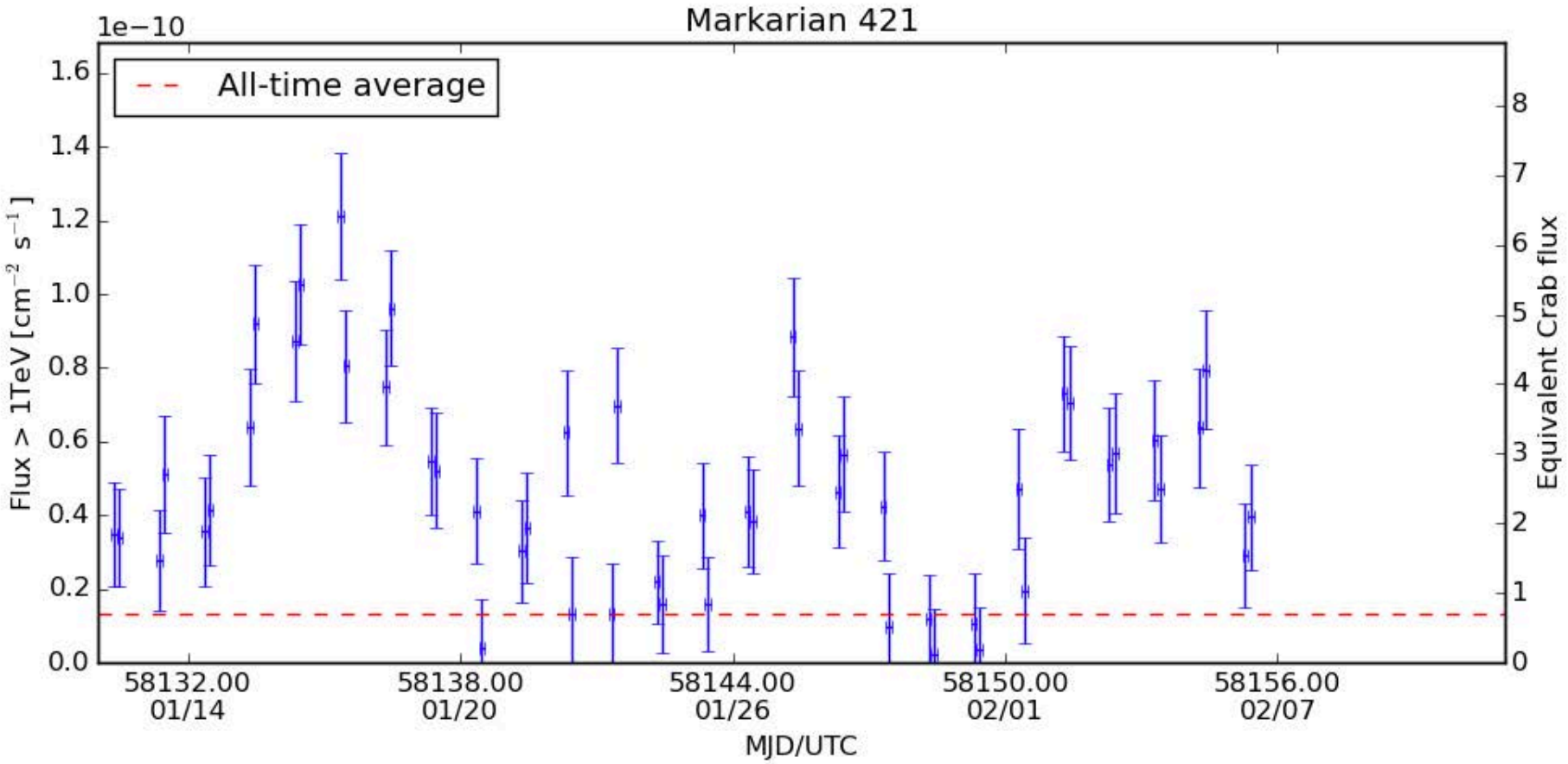
April 8, 2016

Monitoring all gamma-ray sources visible to HAWC every day.

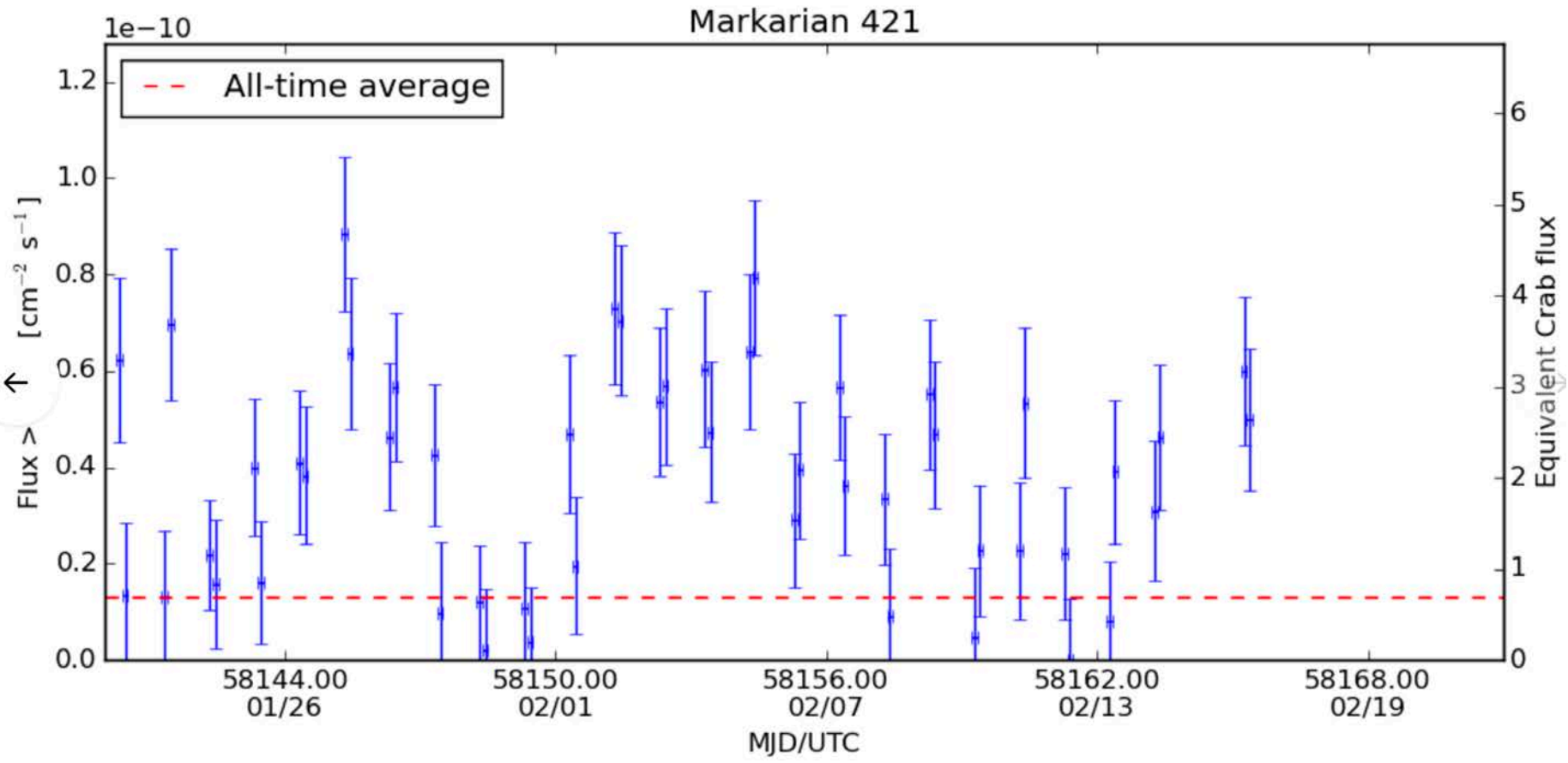
Mrk421 Starting 12-13-2017



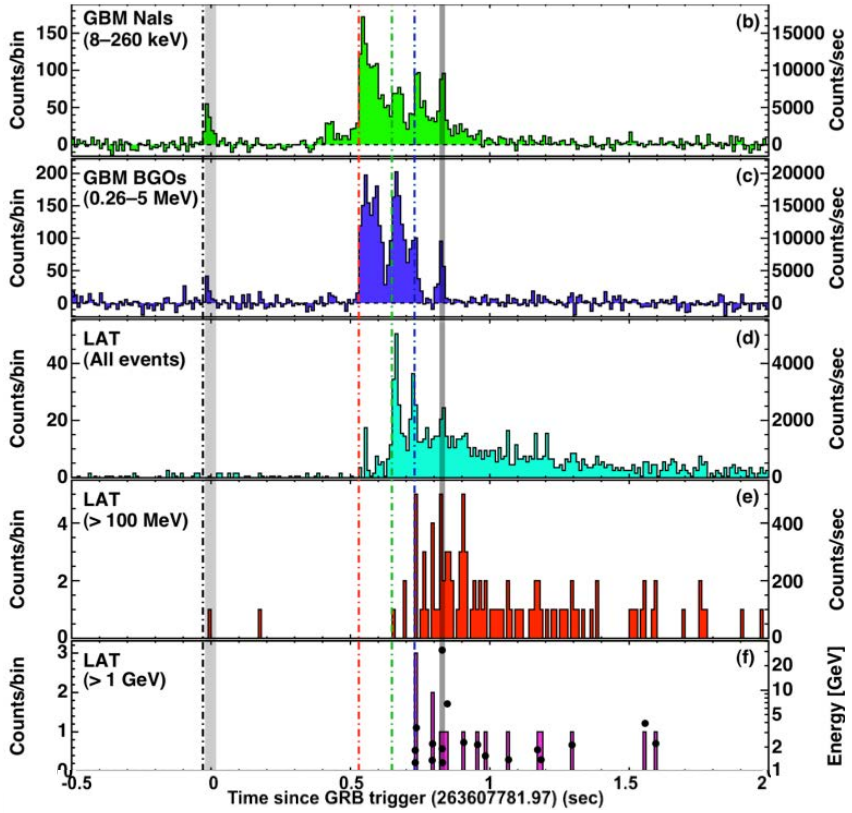
Mrk421 Starting Jan 2018



Mrk421 Up to Today



Fermi Observation of GRB 090510

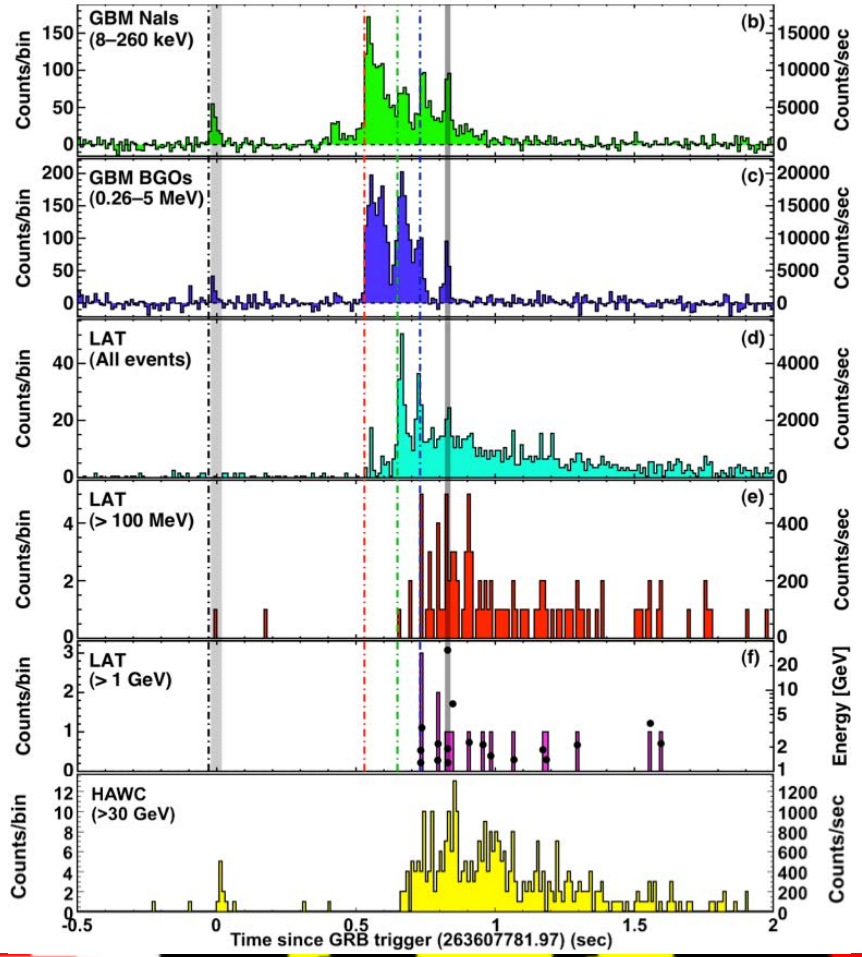


Fermi Observation of GRB 090510 with

- Assume spectrum extends to 125 GeV and attenuation with EBL model of Gilmore
- HAWC: 200 events from GRB 090510 if near zenith

  ~few background events
- Major Improvements!
  - Low-threshold DAQ
  - 10-inch PMTs

→ HAWC would observe 100s of events for spectrum to only 31 GeV

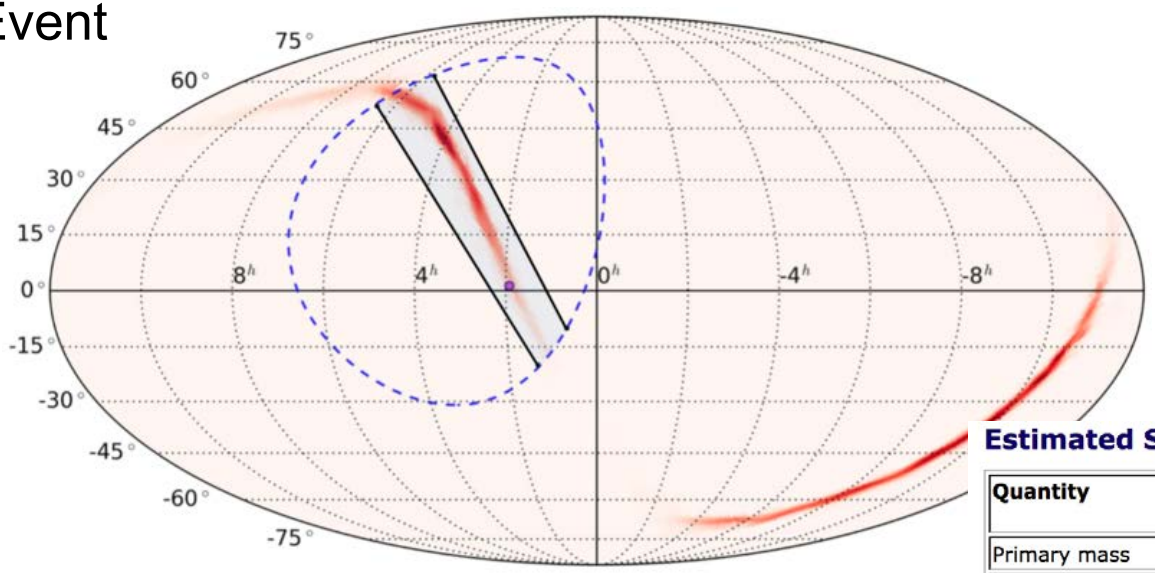


LIGO Events

- Responding to LIGO events
  - First event was below our horizon
- Before VIRGO weveloped algorithm to look in a region
  - Analysis searches for excess counts over the steady-state cosmic-ray background using 4 sliding time windows (0.1, 1, 10, and 100 seconds) shifted forward in time by 10% their width over the course of the entire day.

LIGO Follow-up

Boxing Day Event



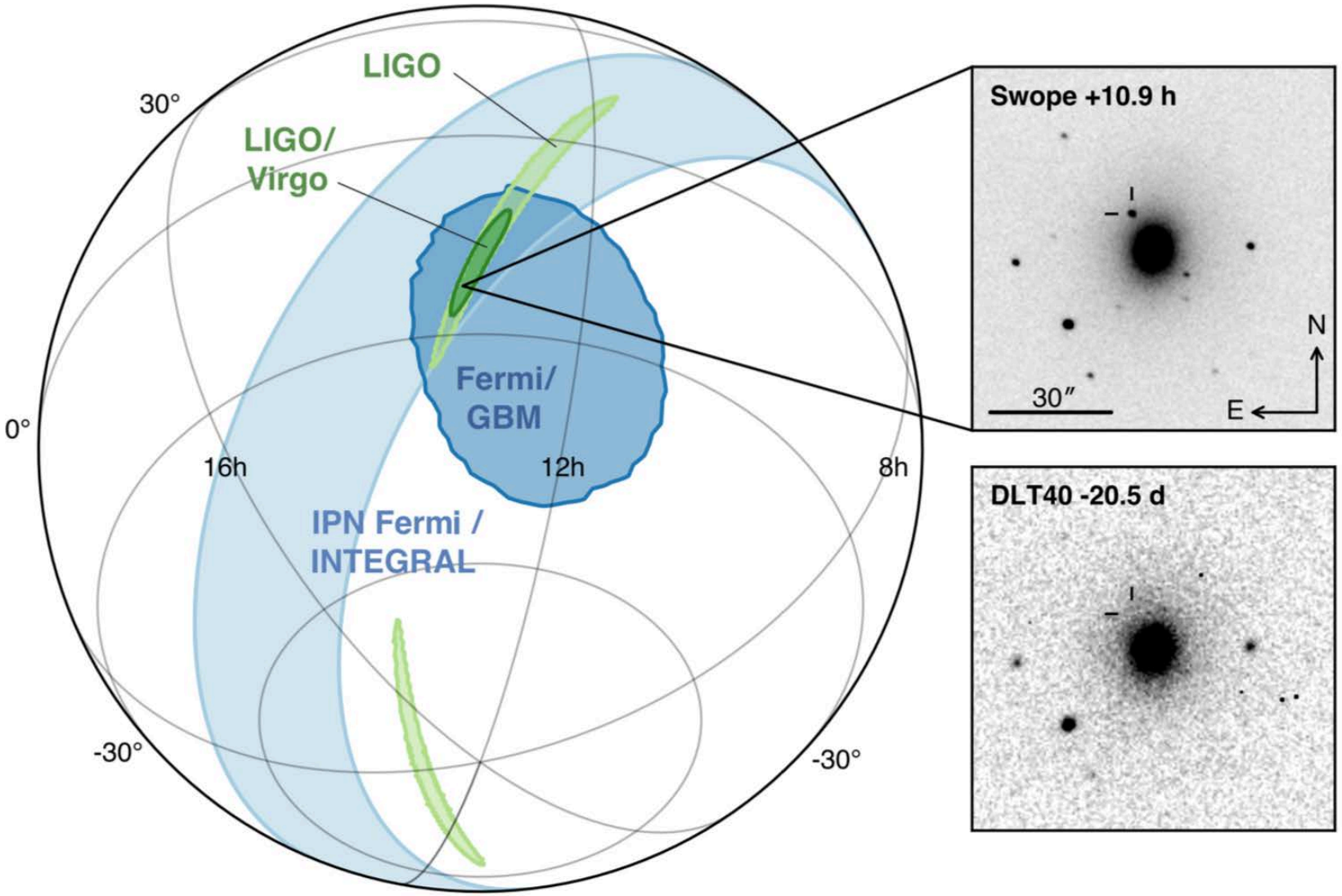
Candidate 1:
RA: 28.628 (+01h 54m 30.63s) J2000
Dec: +1.200 (+01d 11' 59.1") J2000
Error: +1.15 (square region, half side)
Duration: 10 seconds
Pre-trials p-value: 2.55e-07
Post-trials p-value: 0.08

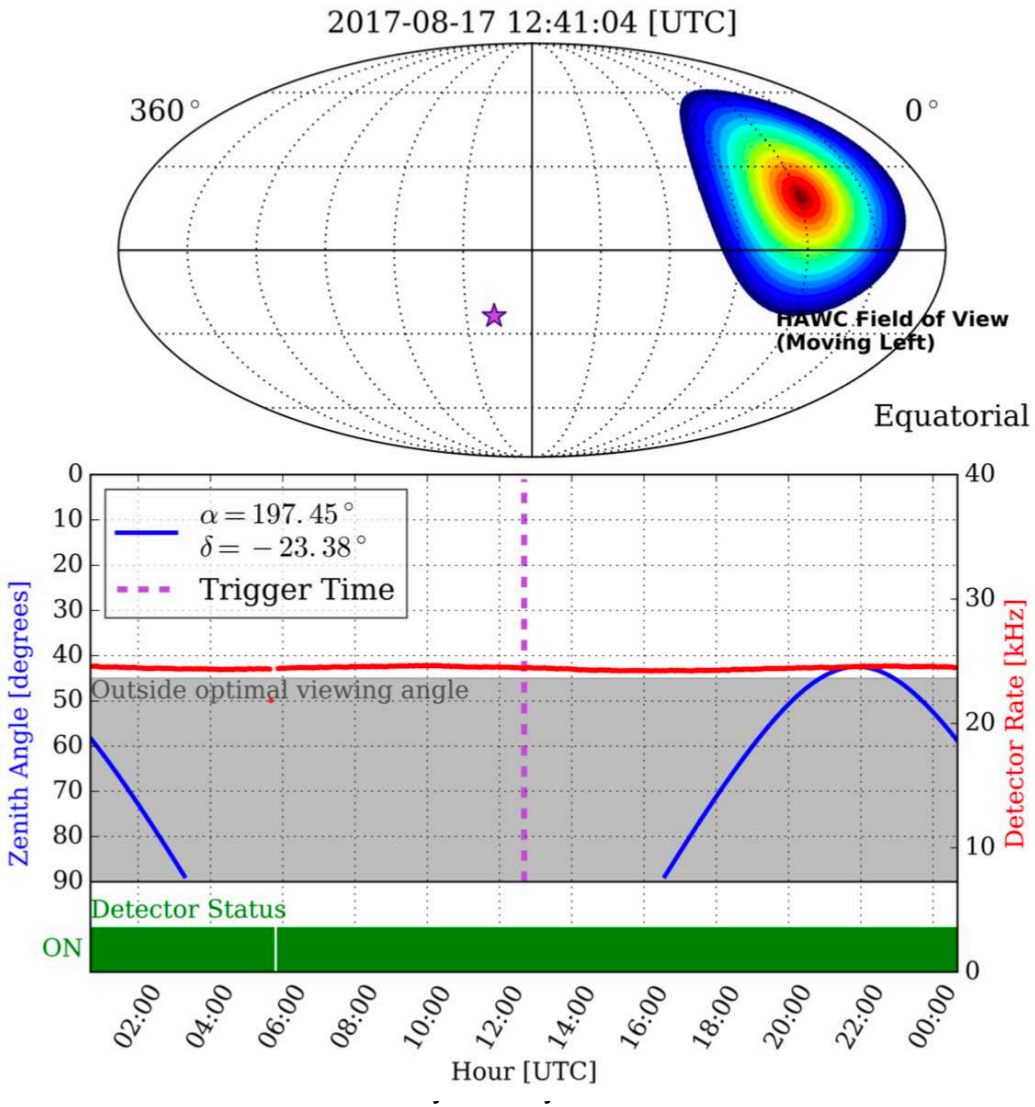
Estimated Source Parameters

Quantity	Value	Upper/Lower error estimate	Unit
Primary mass	**14.2**	+8.3 -3.7	M sun
Secondary mass	**7.5**	+2.3 -2.3	M sun
Chirp mass	**8.9**	+0.3 -0.3	M sun
Total mass	**21.8**	+5.9 -1.7	M sun
Final mass	**20.8**	+6.1 -1.7	M sun
Final spin	**0.74**	+0.06 -0.06	
Radiated gravitational-wave energy	**1.0**	+0.1 -0.2	M sun c^2
Peak luminosity	**3.3**	+0.8 -1.6	10^{56} erg/s
Luminosity distance	**440**	+180 -190	Mpc
Source redshift z	**0.09**	+0.03 -0.04	

The LIGO event of August 17, 2017

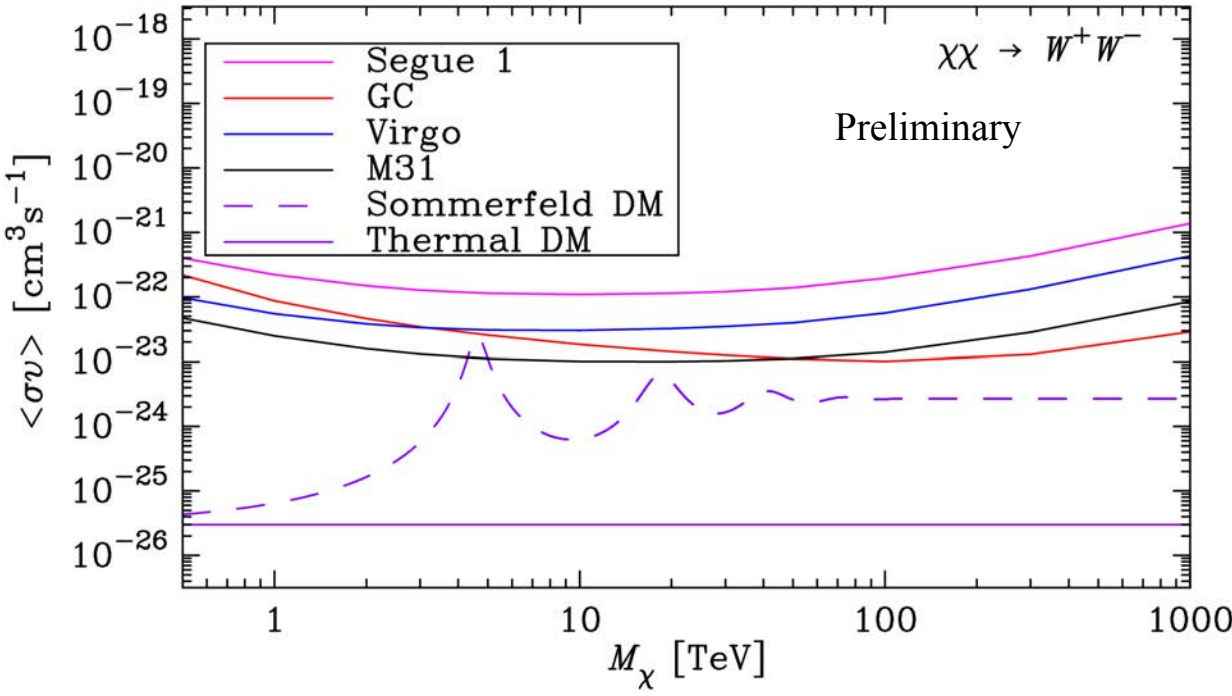
Merging Neutron Stars


LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
30°
0°
-30°
16h
12h
8h
-30°
Swope +10.9 h
30″
N
E
DLT40 -20.5 d

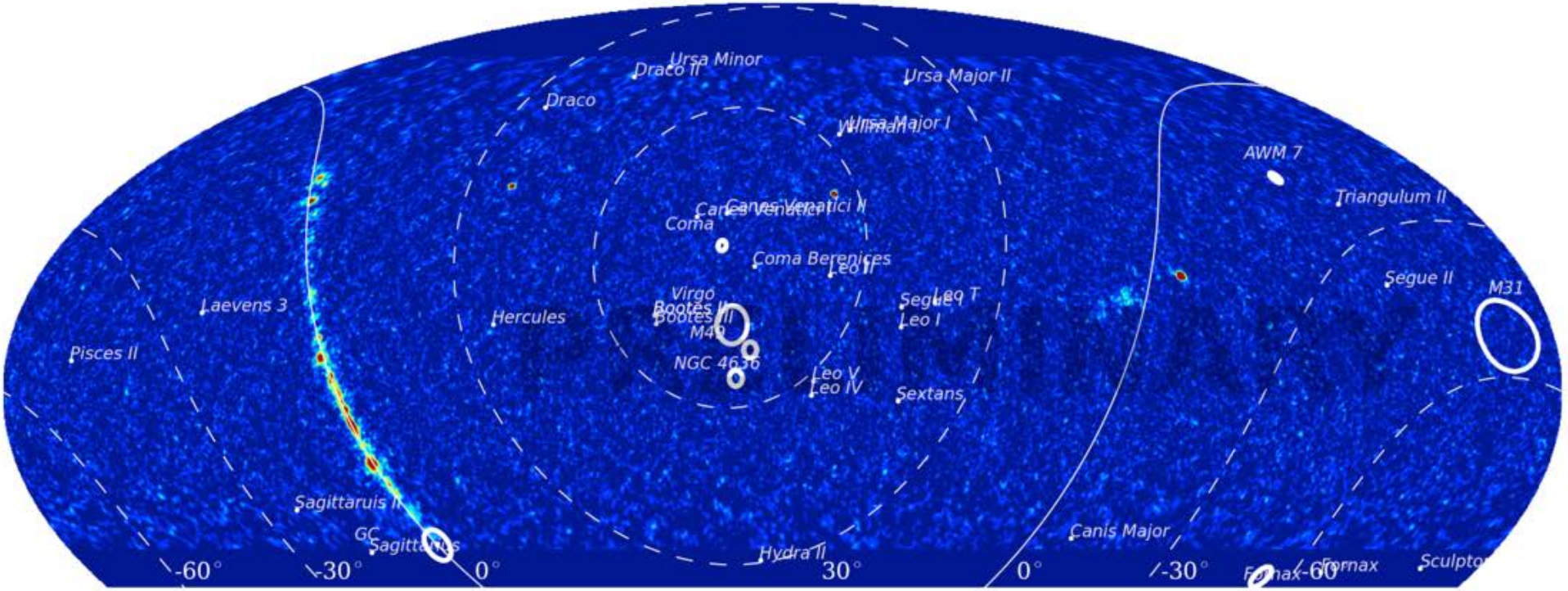

2017-08-17 12:41:04 [UTC]
360°
0°
HAWC Field of View
(Moving Left)
Equatorial
$\alpha = 197.45°$
$\delta = -23.38°$
Trigger Time
Outside optimal viewing angle
Zenith Angle [degrees]
Detector Rate [kHz]
Detector Status
ON
Hour [UTC]
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
00:00

HAWC: Dark Matter

- HAWC has sensitivity to indirect detection of TeV WIMPs in:
  - Satellite galaxies, the Galactic Center, and galaxy clusters
- Cosmological simulations predict more satellite galaxies than observed
  - Higher M/L galaxies have been found by Sloan Deep Survey
  - HAWC will observe all M/L galaxies in half the sky, ***even if L=0***



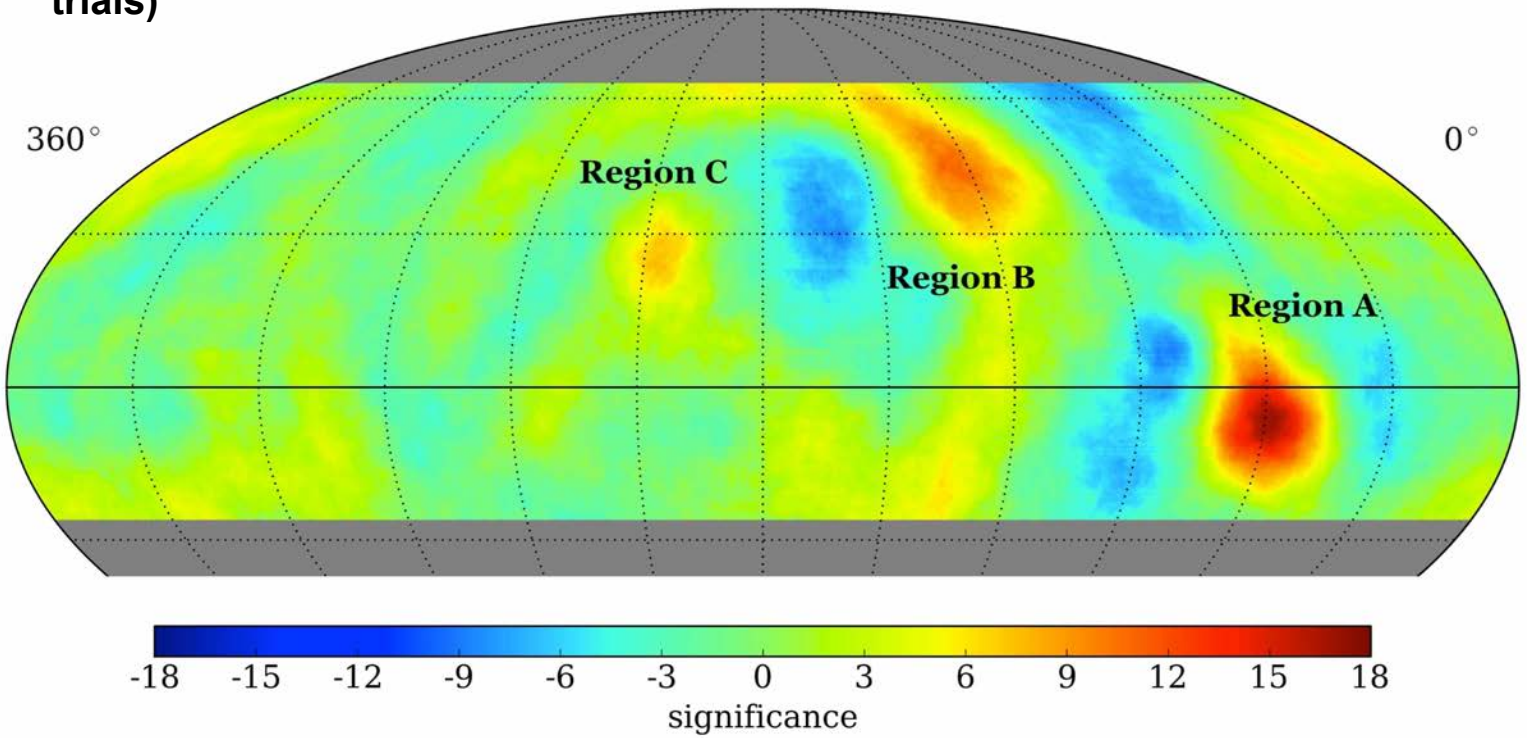
Lots of Potential Targets



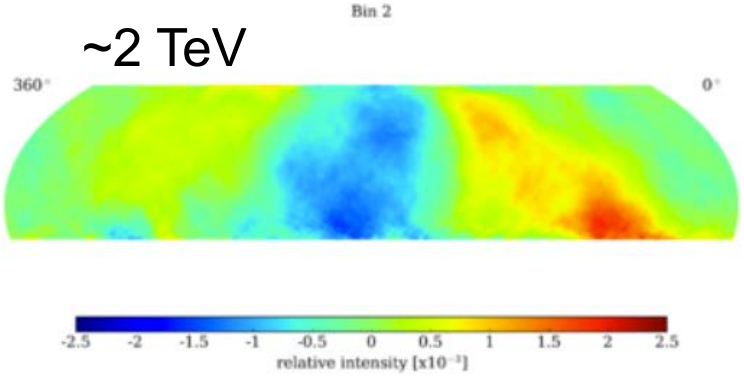
Anisotropy

Fit dipole+quadrupole+octupole to map for 24-hr background estimation
Subtracted fit relative intensity from 24-hr map

Regions A, B and C are the only statistically significant excesses (>5σ post-trials)

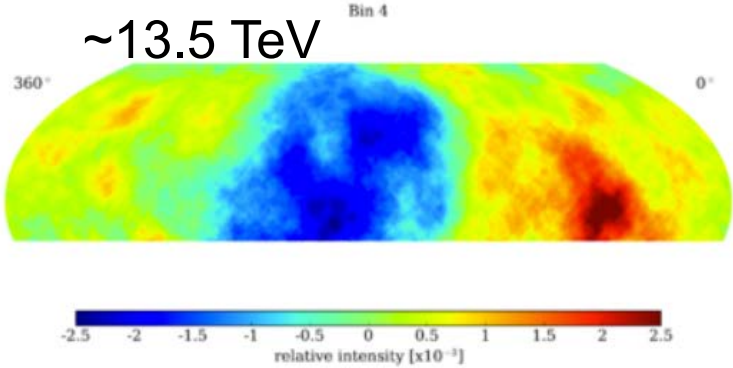


~2 TeV



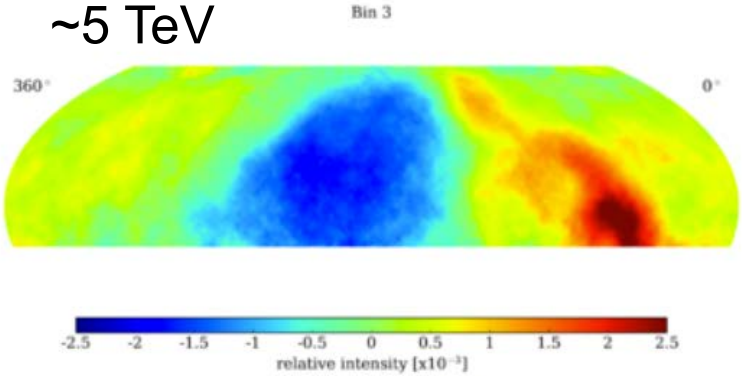
- Large-scale anisotropy for energy bin 2. Median energy is 1.86 (+ 3.03, -1.54) TeV

~13.5 TeV



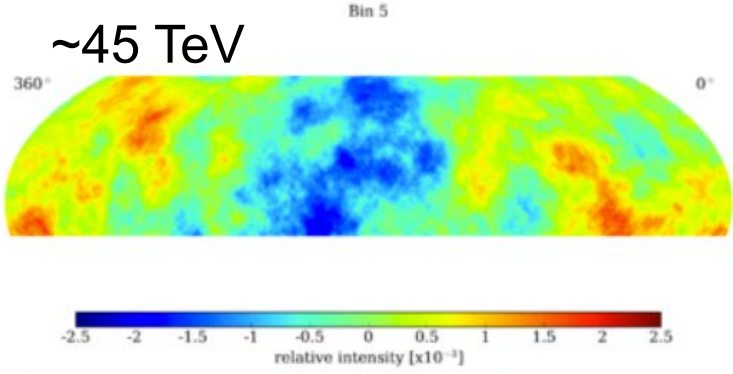
- Large-scale anisotropy for energy bin 4. Median energy is 13.5 (+ 16.0, -9.03) TeV

~5 TeV



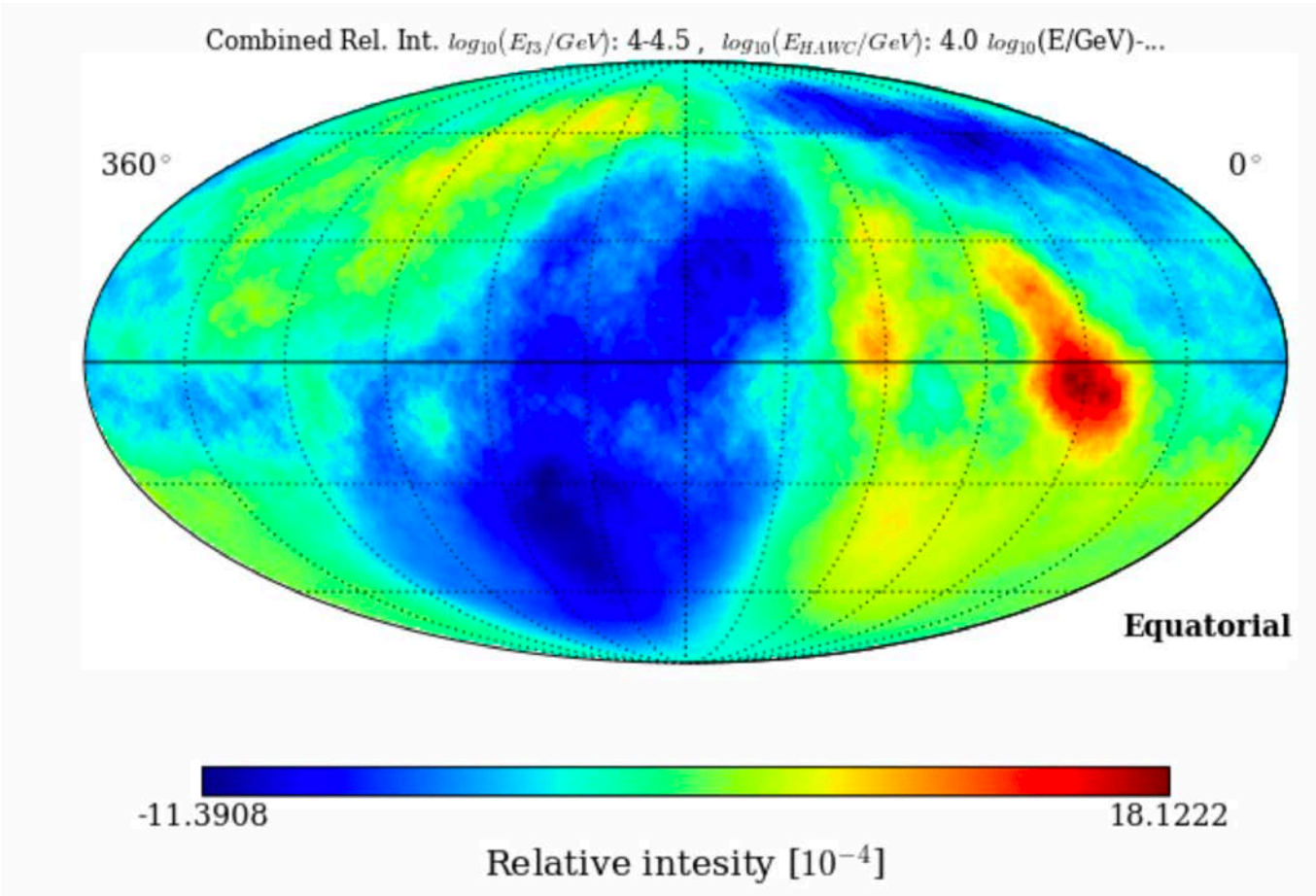
- Large-scale anisotropy for energy bin 3. Median energy is 4.90 (+ 6.85, -3.35) TeV

~45 TeV



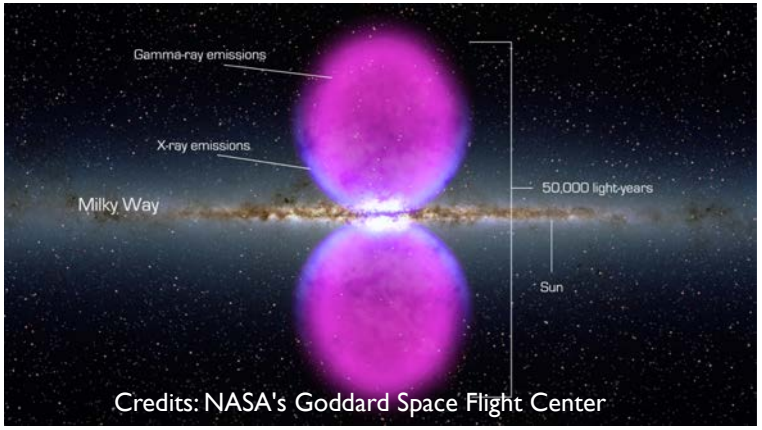
- Large-scale anisotropy for energy bin 5. Median energy is 44.7 (+ 67.6, -27.7) TeV

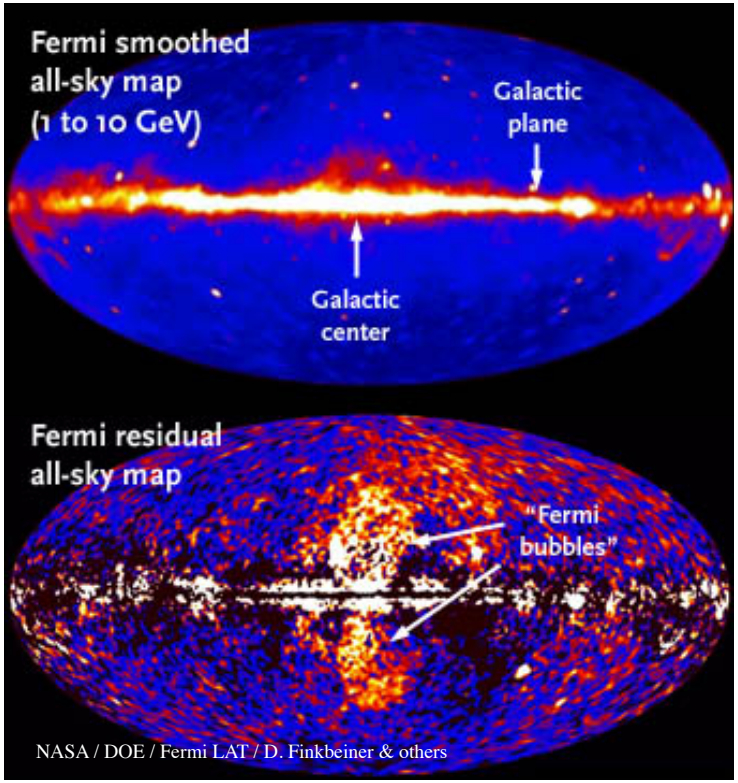
HAWC IceCube Joint Fit



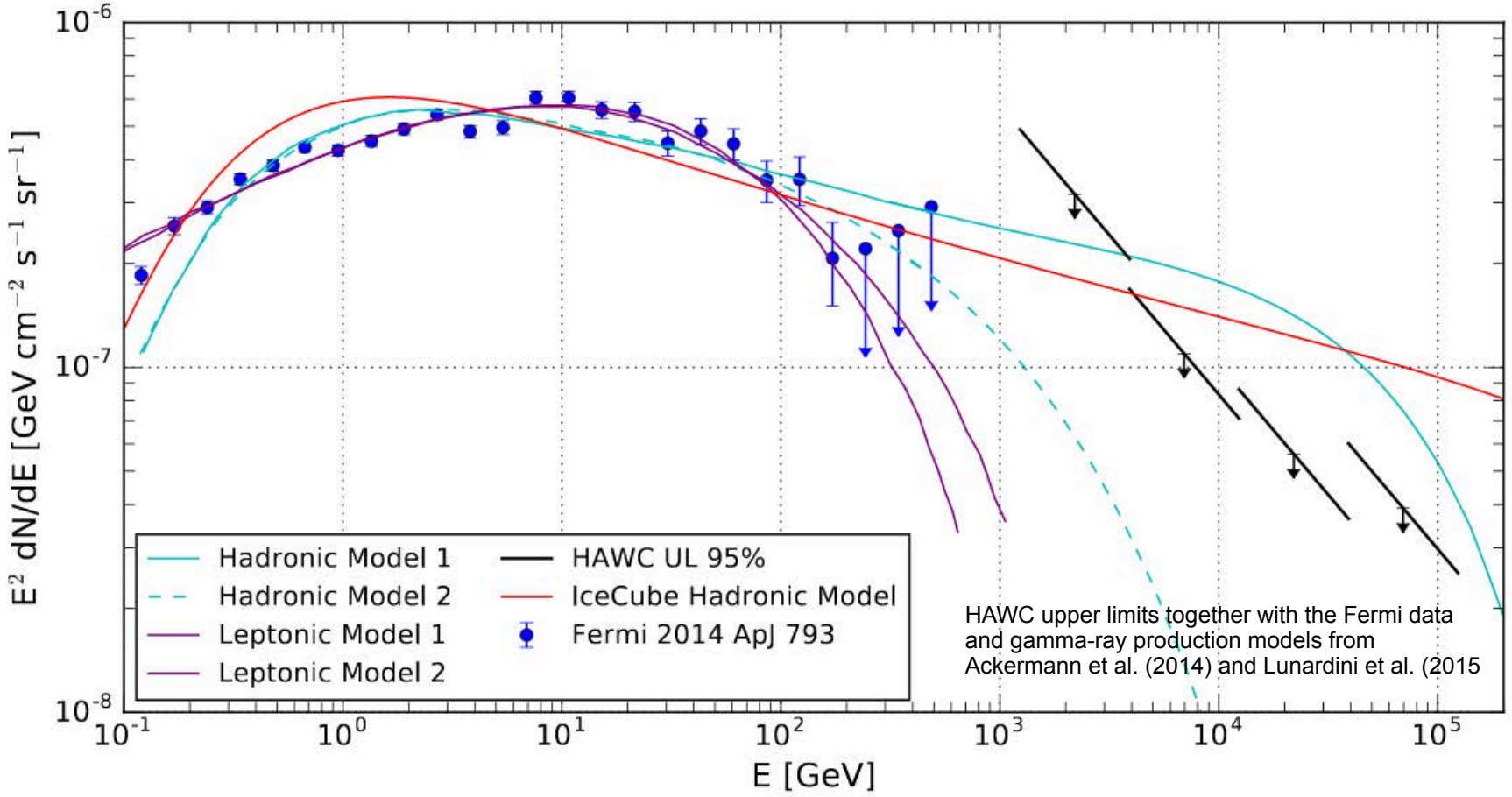
Large-scale structures e.g. Fermi Bubbles

- Large scale, non-uniform structures extending above and below the Galactic center.
  - Edges line up with X-ray features.
  - Correlate with microwave excess (WMAP haze)
  - Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.
- First limits in TeV, **hard spectrum is highly unlikely.**





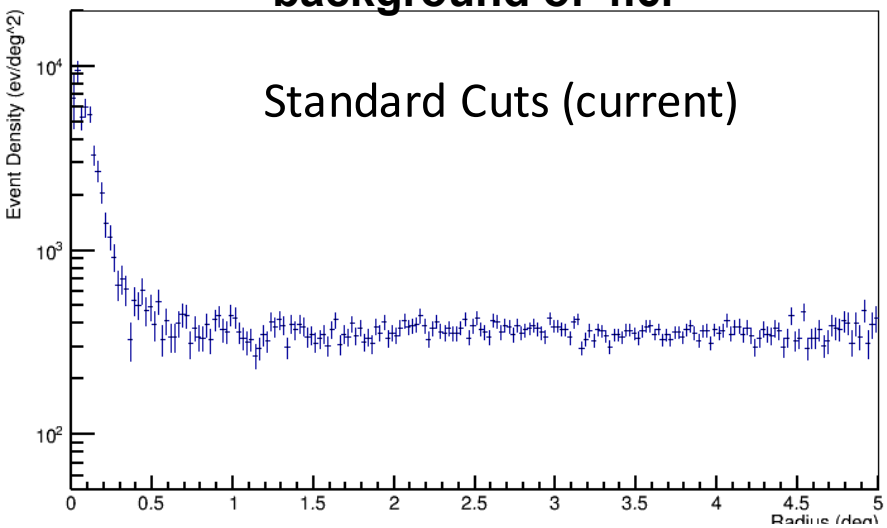
HAWC 90%CL upper limits

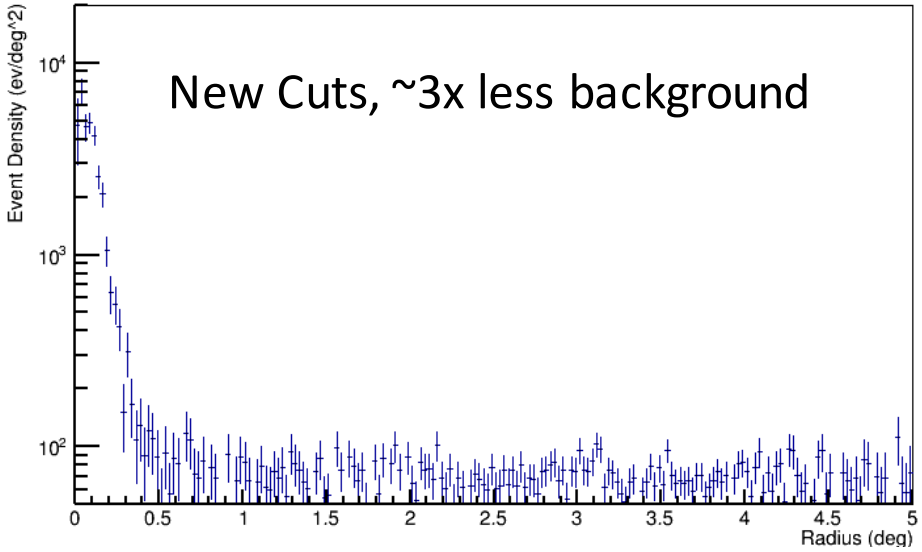


HAWC upper limits together with the Fermi data and gamma-ray production models from Ackermann et al. (2014) and Lunardini et al. (2015

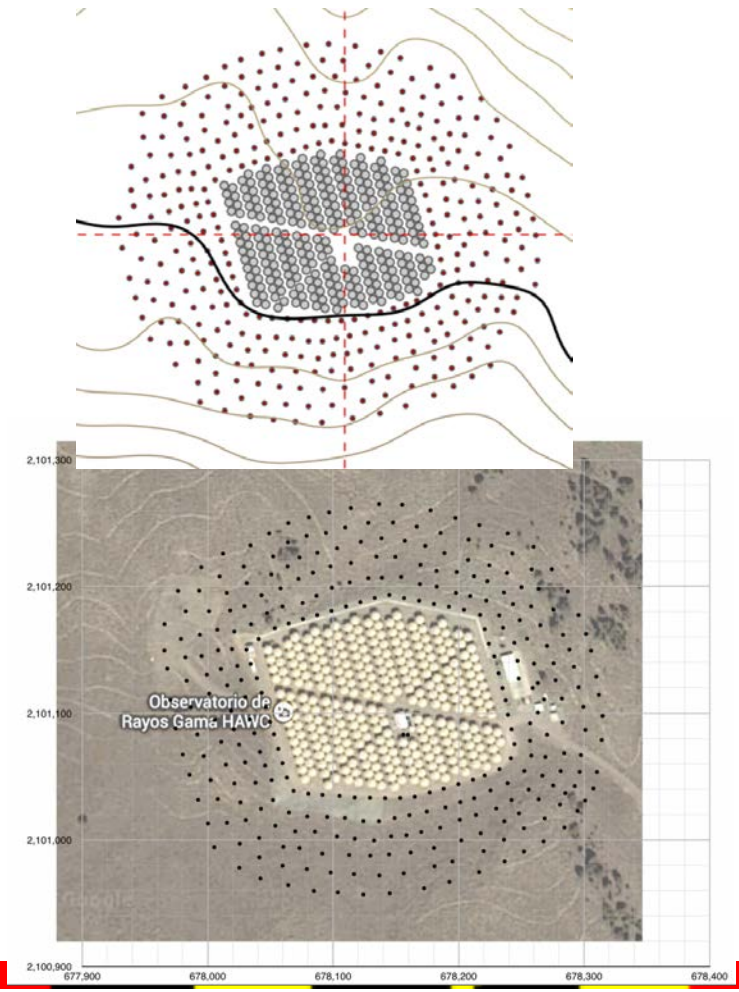
Improvements to HAWC

Using standard cuts on high energy events from the Crab, we observe an excess of 183.6 events with a background of 12.4. Using our improved algorithms we get an excess of 193.4 with a background of 4.6.

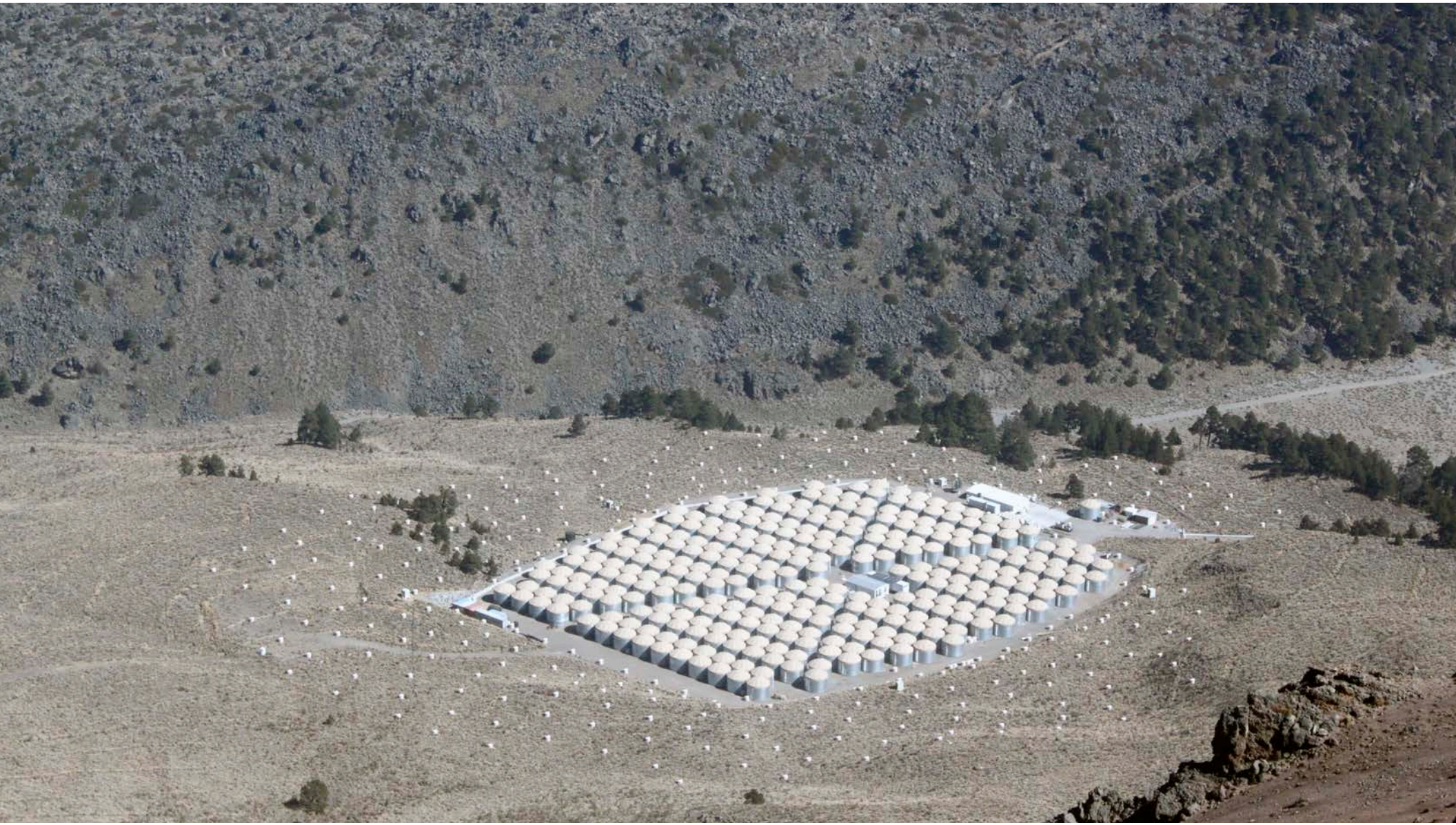




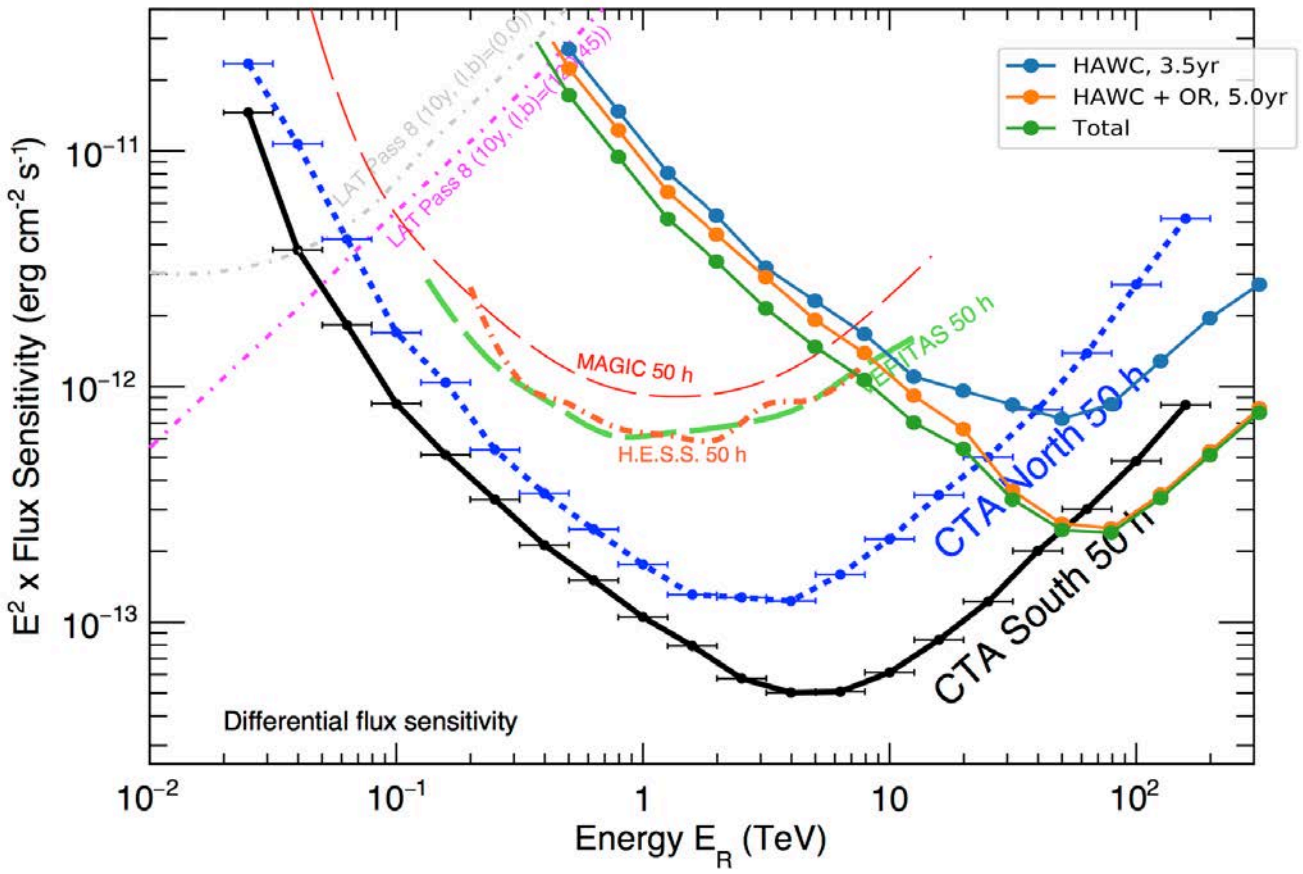
Outriggers



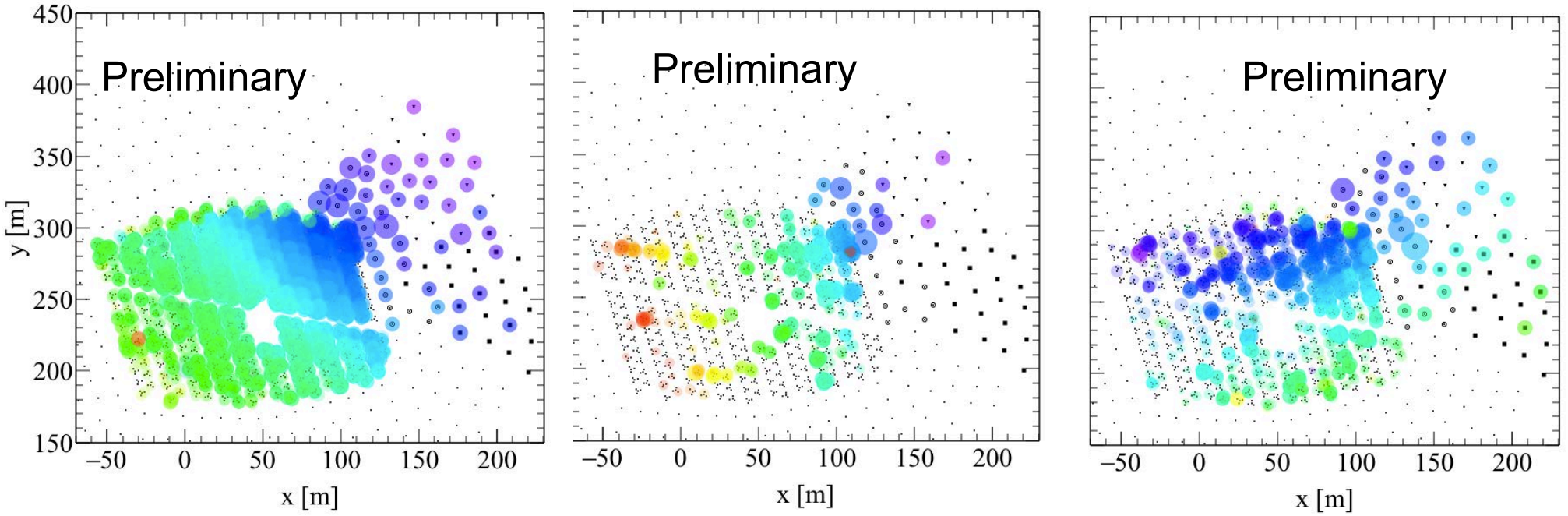
- HAWC Sparse Outrigger Array being deployed now:
  Enhanced Sensitivity above 10 TeV
  - Accurately determine core position for showers off the main tank array.
  - Increase effective area above 10 TeV by ~4x
- Funded by LANL/MPIK (Heidelberg)/Mexico.
- 2500 liter tanks: 1/80th size of HAWC tanks.

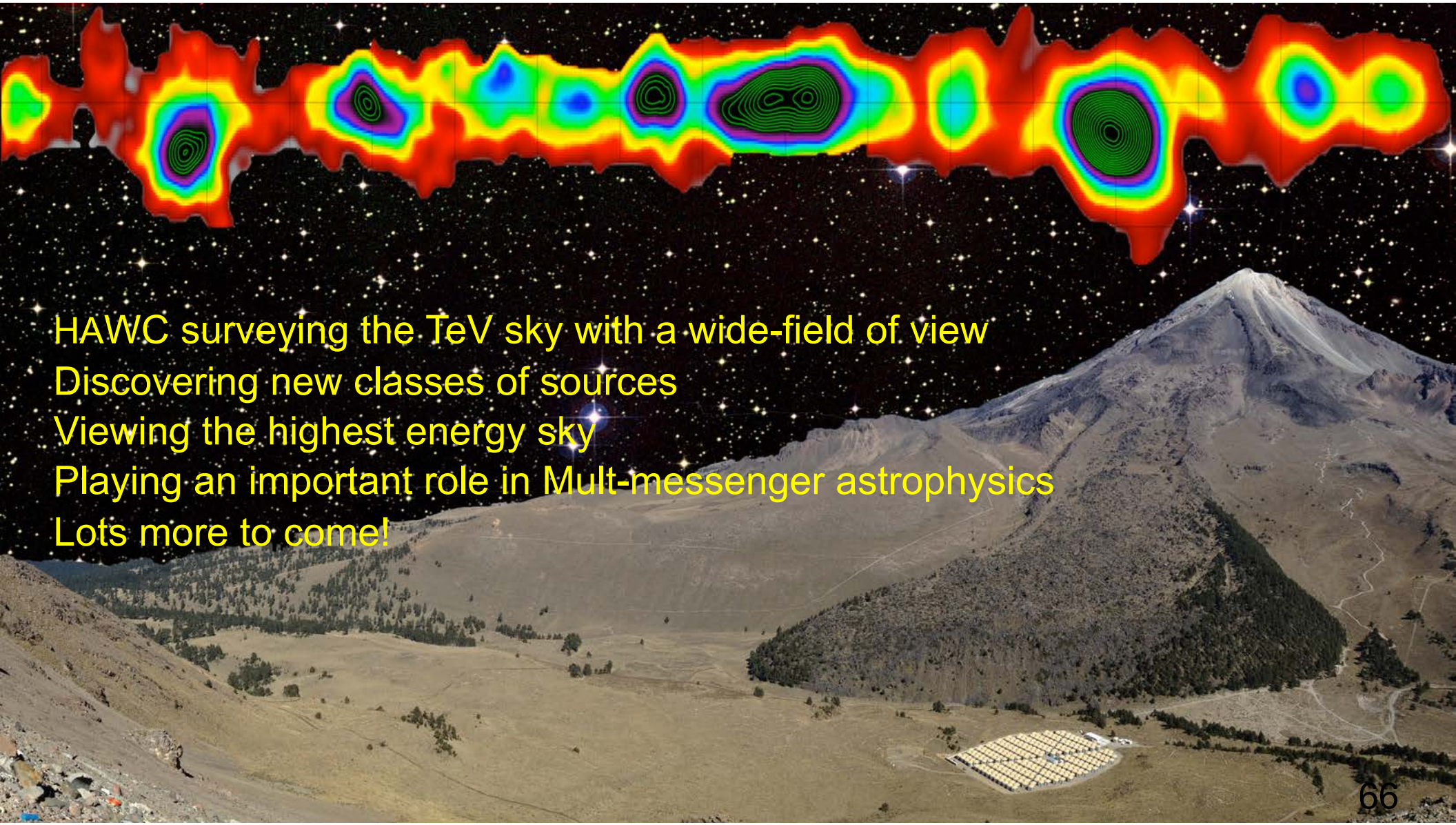


HAWC with Outriggers



Outrigger events Node A (not fully calibrated)




HAWC surveying the TeV sky with a wide-field of view
Discovering new classes of sources
Viewing the highest energy sky
Playing an important role in Mult-messenger astrophysics
Lots more to come!